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THE PRECIPITATION DAY STATISTIC

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ABSTRACT

The first-order station annual totals of days with measurable precipitation are examined and found to be normally distributed. Isoline charts of annual means and standard deviations for the contiguous United States are presented, and quantitative guides used for isoline smoothing are described. The tendency of substation values toward lower means and greater dispersion is noted. The suggestion is made that more reliable probability statements of measurable precipitation occurrence can be obtained through use of the mean and standard deviation charts than from using substation data.

1. INTRODUCTION

The purpose of this paper is to develop charts that show the means and deviations of the annual number of days with measurable precipitation for the contiguous United States. In earlier work on the problem attempts have been made to use data from the substation or cooperative observer network that the U.S. Weather Bureau has operated throughout its existence. This network consists, in the main, of unpaid observers equipped with non-recording rain gages and, sometimes, other meteorological instruments. Over 11,000 such stations, manned by public-spirited citizens, presently provide supplementary weather information of incalculable value to the nation. However, the earlier work using data from this dense network revealed a bias in the substation precipitation day statistic.

Thirty years ago Armington [1] reported that counts of days with measurable precipitation at cooperative stations seemed consistently lower in all parts of the United States than comparable figures for first-order Weather Bureau stations. This was contrary to his expectations, and he could offer no explanation for it.

In 1953, during the course of other work the writer and two co-workers encountered the same bias, although it seems likely that others must have noticed it during the quarter-century interim. After the 1921–52 averages for several climatological items were plotted on base maps for South Carolina, it became apparent that the substation averages of days with 0.01 inch or more did not fit the rather smooth pattern formed by the same statistic for first-order stations. Further, the substation values very frequently disagreed, sometimes violently, with those printed for an earlier period in the 1930 edition of Bulletin W [2].

A few machine runs of punched data cards, which happened to be available at that time for several Missouri stations for a long record period, served to check this finding. The substation bias seemed to persist from the 0.01-inch or more threshold through the 0.02- and 0.03-inch thresholds, and began to weaken at about the 0.04- or 0.05-inch level. The final result of this little study [3] appears as table 1 in which the bias fade shows fairly clearly, except that the intermediate 0.02- through 0.04-inch values are not given. The rest of this earlier work is not presented here because it is no longer available. However, the substation bias will be discussed later in this paper.

These findings led to abandoning this statistic for substations, and, beginning in 1954, to substituting the 0.10-inch threshold for the 0.01-inch threshold for substations in current climatological publications. The 0.01-inch threshold was retained only for first-order stations.

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TABLE 1.—*Average annual number of days with precipitation (1918–1947)*

Station	<.01	≥.01	≥.05	≥.10	≥.15	≥.20	≥.25	≥.30	≥.35	≥.40	≥.45	≥.50
Illinois:												
Cairo*	252.5	112.5	84.7	71.2	61.2	53.7	47.8	41.9	38.3	34.7	31.3	27.7
Missouri:												
Jackson	268.0	97.0	84.7	73.7	64.9	58.8	52.7	46.8	42.7	39.4	35.6	32.7
Columbia*	255.0	110.0	81.9	68.3	58.8	51.6	45.6	40.4	36.0	32.3	29.1	25.9
Mexico	263.4	101.6	86.9	71.6	61.0	54.0	48.0	41.9	37.6	34.1	31.1	28.2
Macon	270.0	95.0	80.2	67.4	57.0	50.4	44.5	39.7	34.9	31.1	27.4	24.8
Marshall	282.3	82.7	75.8	64.8	55.7	50.6	45.0	41.1	35.8	32.0	28.9	26.6
Eldon	274.8	90.2	78.2	67.0	58.8	51.8	46.4	42.0	37.7	33.4	30.0	26.7
Kansas City*	261.5	103.5	75.0	60.5	51.6	45.6	40.5	37.0	33.2	29.6	26.4	23.8
Harrisonville	272.3	92.7	76.3	64.2	56.2	49.5	43.4	39.2	35.3	31.4	28.0	25.8

*First-order stations.

2. GAUSSIAN APPROXIMATION

In approaching this problem more recently, the writer postulated a Gaussian distribution fit to the unbiased annual total days with 0.01 inch or more of precipitation for any one station. The usual curve fitting methods were employed and the not unexpected results showed the normal curve to be an excellent approximation to first-order station data. Several substations were included in the tests as a matter of curiosity, and, although it was not expected, their data proved normally distributed also; the means, of course, were low, but this did not seem to disturb the Gaussian fit.

For this paper, a first-order station network of 169 stations was selected, and the individual annual 1929–58 total days with 0.01 inch or more of precipitation were extracted to provide a uniform 30-year record for all but four stations: Alamosa, Colo., 1933–58; Blue Canyon, Calif., 1930–58; Butte, Mont., 1929–30, 1932–58; Astoria, Oreg., 1929–48, 1950–58. The mean, $\bar{}$, and standard deviation, s, were calculated for each station, and the results appear in table 2. The Kolmogorov-Smirnov goodness-of-fit test, described by Massey [4], was used to prove the Gaussian fit instead of the classical chi-square test devised by Karl Pearson about 60 years ago. Not only was the Kolmogorov-Smirnov test easier to apply in this case, but it is at least as powerful [4] as the chi-square while its use avoids some of the inherent weaknesses of the chi-square test [5] which arise from the arbitrary decisions necessary to its application. There are, of course, still other tests for normality available in addition to these two.

It seemed sufficient to test only one station in each State for normality. For all of these the fit to the normal was proved at the 0.20 significance level, which is excellent. This should be interpreted as meaning that the data for none of the tested stations deviated from a fit to the normal distribution by as much as the very small amount allowed, whereas it would have been permissible for up to 20 percent of the stations to exceed this severe deviation limit and still make the fit-to-normal assumption acceptable. Although it is not particularly important here, one can make the point that the fit is probably not quite that good since it was necessary to use estimates, i.e., the table 2 values, of the distribution parameters. This has the

TABLE 2.—*Station list, means ($\bar{x}$) and standard deviations (s) of annual days with 0.01 inch or more precipitation*

	$\bar{x}$	s
ALABAMA:		
Birmingham	117.9	12.30
Mobile	116.0	12.24
Montgomery	111.7	12.23
ARIZONA:		
Flagstaff	80.2	14.82
Phoenix	35.6	9.16
Prescott	66.1	13.84
Tucson	49.7	9.93
Yuma	16.6	6.60
ARKANSAS:		
Fort Smith	96.3	15.48
Little Rock	104.7	16.83
CALIFORNIA:		
Bakersfield	37.6	8.41
Blue Canyon	85.3	13.07
Eureka	117.9	16.65
Fresno	44.8	8.94
Los Angeles	37.5	9.30
Oakland	63.3	11.22
Sacramento	57.7	11.11
San Diego	44.7	10.86
San Francisco	67.1	13.03
COLORADO:		
Colorado Springs	82.3	13.12
Denver	85.6	13.34
Grand Junction	74.1	14.44
Pueblo	60.8	11.58
CONNECTICUT:		
Hartford	129.2	11.66
New Haven	130.2	11.59
DISTRICT OF COLUMBIA:		
Washington	119.8	12.10
FLORIDA:		
Apalachicola	105.7	14.03
Fort Myers	117.8	15.37
Jacksonville	119.0	11.87
Key West	111.6	12.91
Miami	131.7	16.38
Pensacola	110.1	12.83
Tampa	111.1	11.78
GEORGIA:		
Atlanta	115.5	12.06
Augusta	108.4	12.32
Macon	111.5	11.39
Savannah	108.9	13.11
IDAHO:		
Boise	88.0	14.21
Pocatello	94.0	13.59
ILLINOIS:		
Cairo	113.8	12.43
Chicago	120.3	10.12
Peoria	111.1	9.28
Springfield	111.4	9.63
INDIANA:		
Evansville	116.7	9.84
Fort Wayne	129.1	10.17
Indianapolis	125.3	11.88
IOWA:		
Des Moines	102.9	12.59
Dubuque	110.9	12.30
Sioux City	94.3	12.91
KANSAS:		
Concordia	87.8	13.43
Dodge City	76.5	12.32
Topeka	95.3	14.01
Wichita	86.4	17.58
KENTUCKY:		
Lexington	134.4	12.49
Louisville	119.9	11.40
LOUISIANA:		
New Orleans	119.0	12.89
Shreveport	97.8	13.93
MAINE:		
Portland	132.3	17.21
MASSACHUSETTS:		
Boston	126.7	14.34
Nantucket	127.1	9.68
MICHIGAN:		
Alpena	147.3	11.52
Detroit	132.5	10.81
Escanaba	128.0	10.79
Grand Rapids	137.3	12.59
Lansing	139.5	11.39
Marquette	158.0	11.79
S. Ste. Marie	164.0	11.96
MINNESOTA:		
Duluth	122.5	10.64
St. Paul	110.1	11.84
MISSISSIPPI:		
Jackson	105.7	14.68
Meridian	108.7	14.80
Vicksburg	104.5	13.01
MISSOURI:		
Columbia	106.5	12.94
Kansas City	99.6	13.09
St. Joseph	100.0	13.32
St. Louis	109.2	14.33
Springfield	107.9	13.16
MONTANA:		
Butte	105.2	18.24
Havre	89.9	10.79
Helena	97.0	10.21
Kalispell	124.3	15.95
Miles City	87.6	14.33
NEBRASKA:		
Grand Island	81.6	13.45
Lincoln	93.6	12.55
North Platte	82.7	11.85
Omaha	93.8	12.04
Valentine	88.7	15.43
NEVADA:		
Reno	50.0	10.77
NEW HAMPSHIRE:		
Concord	124.9	13.06
NEW JERSEY:		
Atlantic City	118.9	11.76
Newark	122.6	12.94
Trenton	122.5	11.73
NEW MEXICO:		
Albuquerque	57.9	13.81
Roswell	51.9	13.19
NEW YORK:		
Albany	135.2	12.81
Binghamton	157.4	13.59
Buffalo	161.8	10.99
New York	122.5	11.31
Rochester	160.0	12.36
Syracuse	172.2	12.62
NORTH CAROLINA:		
Asheville	128.9	12.26
Cape Hatteras	118.9	14.82
Charlotte	115.1	11.58
Greensboro	118.7	12.08
Raleigh	114.5	13.29
Wilmington	117.6	14.37
NORTH DAKOTA:		
Bismarck	92.2	12.61
Devils Lake	104.3	10.79
Fargo	101.9	11.27
Williston	89.4	11.82
OHIO:		
Cincinnati	129.0	13.35
Cleveland	150.8	13.88
Columbus	132.1	10.44
Dayton	127.0	13.03
Sandusky	137.2	11.53
Toledo	128.6	9.95
OKLAHOMA:		
Oklahoma City	82.1	14.37
Tulsa	90.3	14.15
OREGON:		
Astoria	179.5	18.53
Eugene	144.2	18.33
Medford	100.5	13.05
Portland	150.6	18.21
Roseburg	131.0	15.89
PENNSYLVANIA:		
Erie	155.3	14.30
Harrisburg	124.6	12.36
Philadelphia	119.8	11.74
Pittsburgh	150.7	15.05
Reading	124.8	13.76
Scranton	135.2	12.59
RHODE ISLAND:		
Block Island	121.3	11.36
Providence	121.4	13.18
SOUTH CAROLINA:		
Charleston	107.3	14.43
Columbia	110.2	11.02
SOUTH DAKOTA:		
Huron	91.8	10.82
Rapid City	92.9	12.30

TABLE 2.—*Station list, means* ($\bar{x}$) *and standard deviations* (s) *of annual days with 0.01 inch or more precipitation*—Continued

	$\bar{x}$	s
TENNESSEE:		
Chattanooga	121.0	12.96
Knoxville	127.2	12.78
Memphis	104.5	14.93
Nashville	118.5	11.02
TEXAS:		
Abilene	65.2	14.32
Amarillo	67.2	13.26
Austin	84.4	13.50
Brownsville	79.6	15.30
Corpus Christi	78.1	15.77
Dallas	79.0	14.81
Del Rio	60.2	15.25
El Paso	46.4	11.39
Fort Worth	78.2	13.77
Galveston	94.3	11.73
Houston	104.7	12.72
San Antonio	82.7	13.52
UTAH:		
Salt Lake City	90.0	11.57
VERMONT:		
Burlington	149.9	12.68
VIRGINIA:		
Lynchburg	124.7	18.16
Norfolk	119.8	12.59
Richmond	118.7	13.39
WASHINGTON:		
Seattle	150.3	18.14
Spokane	110.1	17.37
Tatoosh Island	197.5	17.45
Walla Walla	106.5	14.86
Yakima	68.0	13.01
WEST VIRGINIA:		
Elkins	168.5	17.31
WISCONSIN:		
Green Bay	116.1	11.05
LaCrosse	112.8	11.60
Madison	116.7	11.66
Milwaukee	115.8	9.82
WYOMING:		
Cheyenne	101.4	12.87
Lander	69.7	11.58
Sheridan	104.0	12.80

effect of reducing further the already narrow deviation limit although the magnitude of this effect is not known [4].

3. CONSTRUCTION OF CHARTS

The station means and standard deviations (table 2) were plotted on charts in order that the smoothed isoline analyses could be made which appear here as figures 1 and 2. Naturally, any analysis of this sort is somewhat subjective, but the problem was made easier by the rather conservative nature of both statistics; i.e., they do not vary as rapidly with horizontal or vertical distance as do many other climatological elements such as total rainfall, temperature, and relative humidity, to name a few. Actually, little isoline smoothing was required, and that which was performed was done with recognition of the sampling error present in the calculated means and standard deviations themselves, and with attention to the major topographic features. The latter practice is familiar to climatologists, but the former may require some explanation.

If a different record period had been used, slightly different values would have appeared in table 2; this would have been true whether another 30-year period had been selected or whether a longer or shorter period had been used. Therefore, the table 2 values are only point estimates of the true values which are always unknown in climatology.

It became desirable, therefore, to obtain some quantitative measure of the possible departures of the means, $\bar{x}$, and standard deviations, s, of table 2 from their true or theoretical counterparts, μ and σ, respectively. This was done by constructing confidence intervals within which the true values must lie a desired portion of the time; i.e., in repeated sampling, a predetermined percentage of the several sets of intervals will contain the true means or standard deviations. This method provided additional isoline smoothing guides which were used wherever there were isoline sinuosities that could not be explained on the basis of topographic influences. The 90 percent confidence interval was selected here, and it was assumed there were no trends in the data.

In calculating the 90 percent confidence intervals for the means in this paper, use was made of the probability statement.

$$P[|\bar{x}-1.64\,s/\sqrt{n}|<\mu]=0.90 \tag{1}$$

where n is the number of years of record (30 in this case), 1.64 is selected from any normal probability table such as [6], and s, $\bar{x}$, and μ are as before. Theoretically, the true standard error (i.e., standard deviation) of the mean $\sigma/\sqrt{n}$ should be used instead of $s/\sqrt{n}$, but the fairly large size of n permits the substitution without significant error here. The correct method, and the one to be used when n is much smaller, makes use of the statistic $t=(\bar{x}-\mu)\sqrt{n}/s$ in which σ does not appear and which has Student's distribution with $n-1$ degrees of freedom. Then the probability statement

$$P[|(\bar{x}-\mu)\sqrt{n}/s|<t]=0.90$$

gives rise to the 90 percent confidence interval $\bar{x}-0.31s<\mu<\bar{x}+0.31s$ after the value of $t=1.699$ is obtained from a table of Student's distribution. The difference here, as can be seen by referring to probability statement (2) below, is insignificant. If the variances are not calculated in their unbiased form $s^2=\Sigma(x_i-\bar{x})^2/(n-1)$ as they are here, $\sqrt{n-1}$ should be inserted in the probability statement above in lieu of $\sqrt{n}$.

After substitution of the proper values in the probability statement (1), the 90 percent confidence interval of the mean becomes

$$\bar{x}-0.30s<\mu<\bar{x}+0.30s \tag{2}$$

Whenever there were isoline irregularities that could be explained on no other basis, inequality (2) was used and the line moved not more than $0.3s$ (which could be interpolated from figure 2 with accuracy sufficient for the purpose) with considerable assurance that no appreciable error was introduced into the analysis thereby.

In order to find the 90 percent confidence intervals for the standard deviation, use was made of the quantity $(n-1)s^2/\sigma^2$ which has a chi-square distribution with $n-1$ degrees of freedom. This form is used in order to be consistent, since the variances were calculated in their unbiased form $s^2=\Sigma(x_i-\bar{x})^2/(n-1)$ as preferred by many experimentalists. Most mathematical statisticians (c.f. [7]) prefer for ease of handling and for class instruction, variances expressed as $\Sigma(x_i-\bar{x})/n$, in which case the above quantity would become ns^2/σ^2. In most cases, the difference is unimportant, as is the case here, particularly when n is fairly large. Then, the assumption was made [8] that the probability is 0.90 that

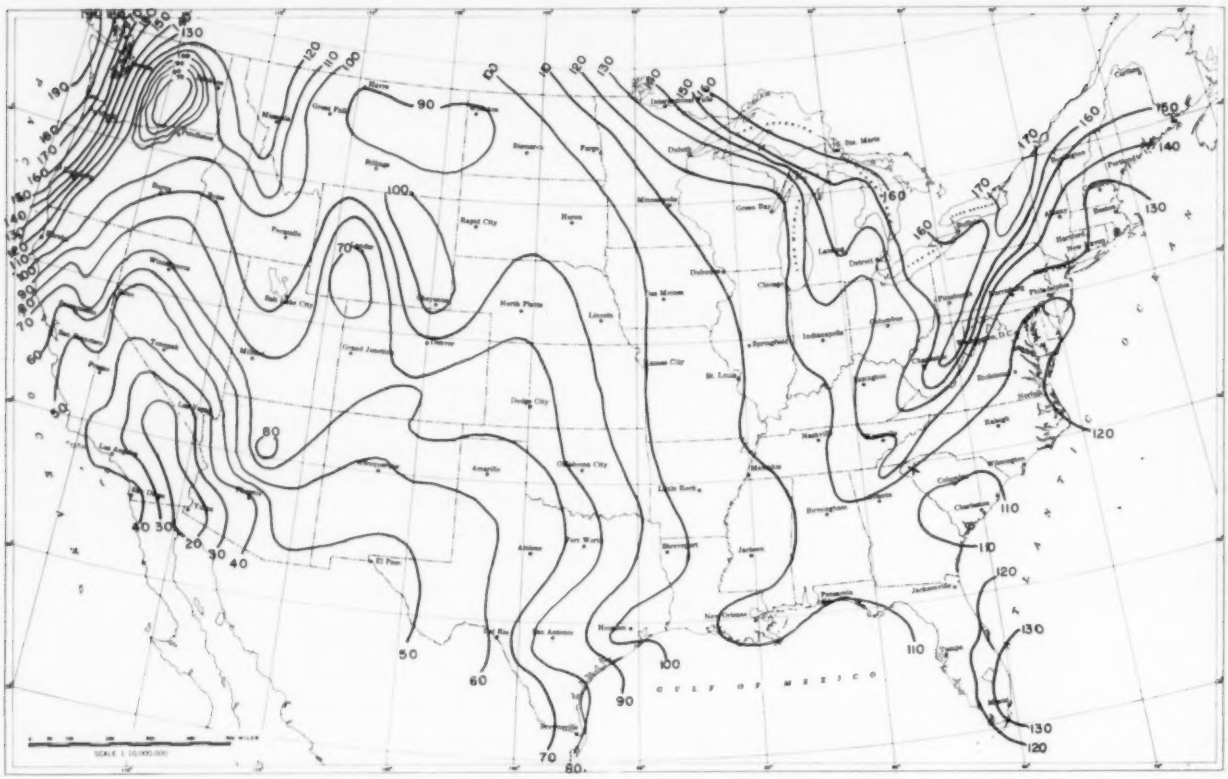

FIGURE 1.—Mean annual number of days with precipitation ≥0.01 inch (1929–58).

$$(n-1)s^2/\chi_2^2<\sigma^2<(n-1)s^2/\chi_1^2 \qquad (3)$$

where n, s, and σ are as before, and the two chi-square values χ_1^2 and χ_2^2 are 17.71 and 42.56 as selected for the 0.90 probability interval from a table of the chi-square distribution such as [6]. After insertion of the proper values and simplification, inequality (3) becomes

$$0.83s<\sigma<1.28s \qquad (4)$$

When necessary, inequality (4) was used in figure 2 in the same manner and for similar reasons that inequality (2) was used in figure 1.

4. USE OF CHARTS

A valuable characteristic of the Gaussian distribution is that it is defined completely by its mean and standard deviation, and it was for this reason that figures 1 and 2 were constructed. Interpolated values obtained from the charts can be used to make probability statements concerning the annual days with 0.01 inch or more of precipitation at any location covered by the charts.

For example, in figures 1 and 2 refer to the large "X" which marks the location of Clemson in the northwestern part of South Carolina. The mean interpolated from figure 1 is about 120 days, and the standard deviation from figure 2 is about 12.2 days. If it must be known, for instance, what the chances are of getting less than 108 days with measurable precipitation at Clemson in any one year, the expression $(x-\bar{x})/s$ is evaluated to obtain the entry value to any table of the normal distribution function, such as that contained in any statistics text or in [6]. In this case, with $x=108$, $\bar{x}=120$, and $s=12.2$, a slide rule calculation gives -0.98 standard deviation, which from [6] corresponds to a probability of 0.1635. Thus, at Clemson there is only a 16 percent chance of having less than 108 precipitation days in any one year; only about 1 year in 6 will have more than $365-108=257$ precipitation-free days; or the chances are about 5 to 1 that there will be more than 108 days with measurable precipitation in a year.

In the steeper mountain areas there are apt to be steep climatic gradients, as every meteorologist knows. Earlier in this paper, a statement was made concerning the conservative nature of the "day with 0.01 or more" statistic. While this is true when compared to some of the other climatic elements, this statistic is certainly not immune to the effects of rapid elevation changes within short horizontal distances. Consequently, only a general-

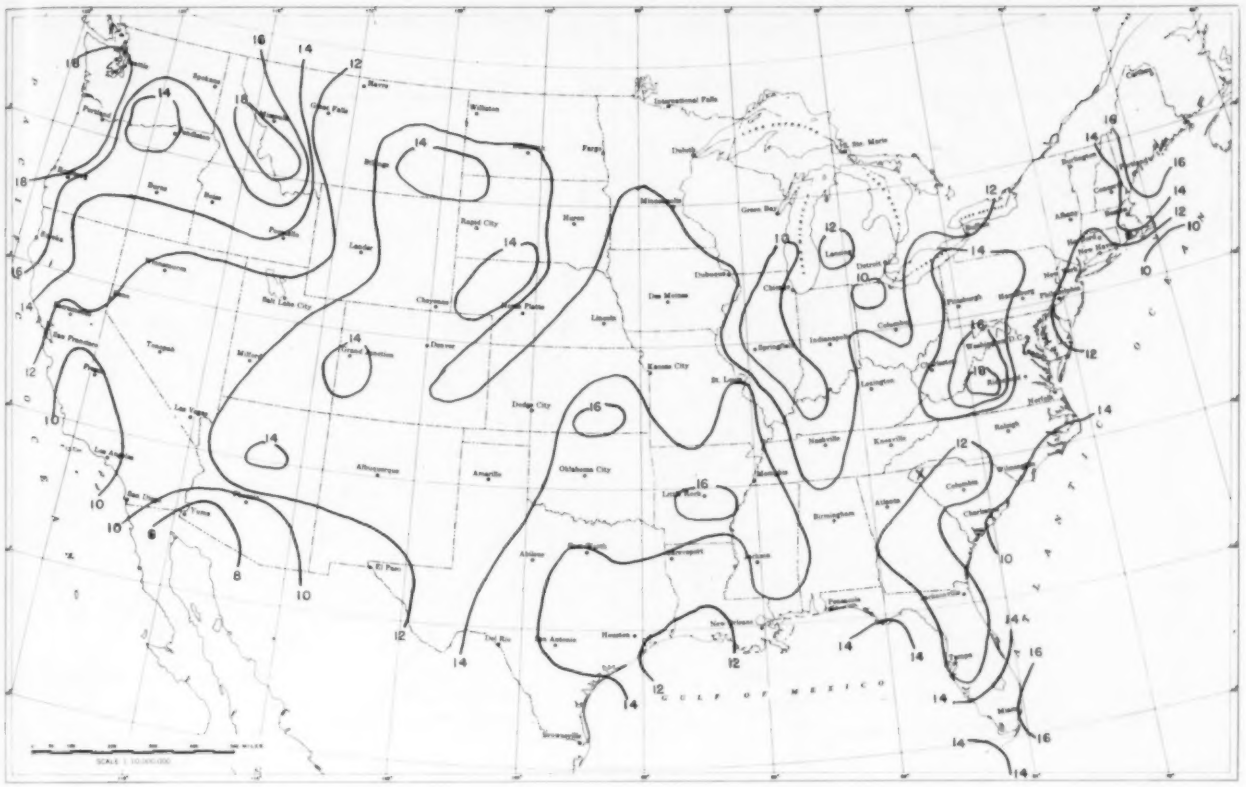

FIGURE 2.—Standard deviation of annual days with precipitation ≥0.01 inch (1929–58).

ized picture could be attempted in figures 1 and 2 over the major mountain areas of the country. For instance, mean values for Stampede Pass, Wash., and Mount Washington, N.H., are about 200 days, which is far above the expectancy shown in figure 1. These are extreme cases, however, and the suggested interpolation procedures should give good accuracy over most of the country.

5. THE SUBSTATION BIAS

Earlier, some introductory statements were made regarding the bias of cooperative station means toward low values as compared to first-order station means. This may be seen by examining figure 3. From data furnished by the Weather Bureau State Climatologist for Georgia, mean values and standard deviations for 45 substations were calculated and plotted on base maps which appear as figures 3 and 4. The isolines, however, were lifted directly from figures 1 and 2 so as to represent an analysis based entirely on first-order station data. Obviously, most substation means appear to be too small and there seems to be little uniformity as to the degree of bias. Furthermore, the substation standard deviations are frequently larger than they should be, showing a considerably greater data dispersion about the means.

Although figures 3 and 4 were based on a 30-year period (ending in 1952), the period is not uniform for each station because of missing record, nor is it the same as the 1929–58 period used for figures 1 and 2. These deficiencies could not be avoided without entailing considerably more data tabulation work, but this seemed unnecessary since the results confirmed the writer's earlier findings in 1953.

Calculations on actual 1929–58 data for Clemson, S.C. [9], produced an annual mean of 99.7 days with a standard deviation of 11.16. Use of these statistics, in the same manner given in the example earlier, gave rise to a 77 percent probability of having less than 108 days with measurable precipitation at Clemson, which value should be compared to the 16 percent probability found earlier. This indicates that, at least in some cases, the use of biased substation data results in less reliable probability statements than can be obtained through use of values interpolated from figures 1 and 2, as previously suggested.

Figure 5 is presented as further evidence of the substation bias. It appeared in [10], and was based on first-order station data as well as on data from several thousand substations. It should be compared with figure 1. Close

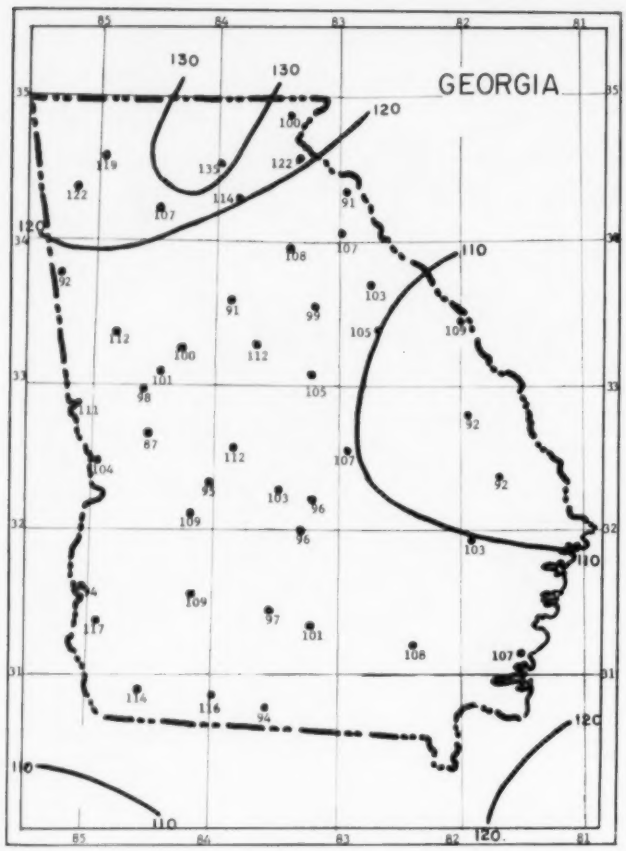

FIGURE 3.—Mean annual number of days with precipitation ≥0.01 inch.

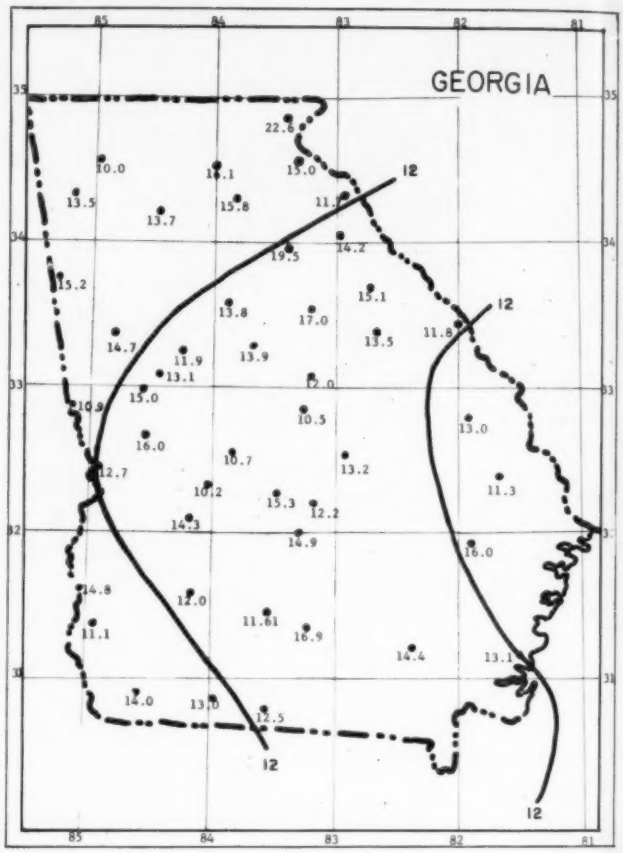

FIGURE 4.—Standard deviation of annual days with precipitation ≥0.01 inch.

inspection of figure 5 reveals the extreme irregularity of the isolines, which the writer regards as suspect, as well as many small closed contours or "islands" of high values. It turns out that many, if not most, of these islands surround a first-order station, and plotting these high-value islands gives a fairly good idea of the first-order station network used.

6. CAUSE OF SUBSTATION BIAS

In the absence of any real information on the substation bias cause, only conjectural statements can be made. To this writer, it seems plausible that the bias is a combination of several effects which probably differ from station to station and from time to time at the same station. Possibly some substation observers may not look in the rain gage each day, not realizing that it may have rained while they were engaged in their regular daily activities. In this manner, small amounts could be missed frequently.

Others, particularly those in the warmer areas, may find that small amounts have evaporated before they make their once-daily inspection of the gage. However, if this were a primary cause, the bias should follow a definite gradient, within an area, which should approximate the evaporation gradient. This does not seem to be the case in any data examined by the writer. For example, reference to Plate 1 of [11] shows that annual average evaporation increases from northern to southern Georgia, but the bias does not follow the same pattern, as will be seen from figure 3, even if changes in the mean values are taken into account as one goes from north to south.

7. FURTHER WORK

Although precipitation day statistics can be extremely useful in planning operations, it is not likely that the 0.01-inch threshold will be as useful as higher thresholds, e.g., 0.10, 0.25, 0.50, 1.00, etc., for most operations. For example, if a contractor bids on a dirt excavation job, he wants to know how many precipitation-days will be exceeded in a year with, say, a 75 percent probability so

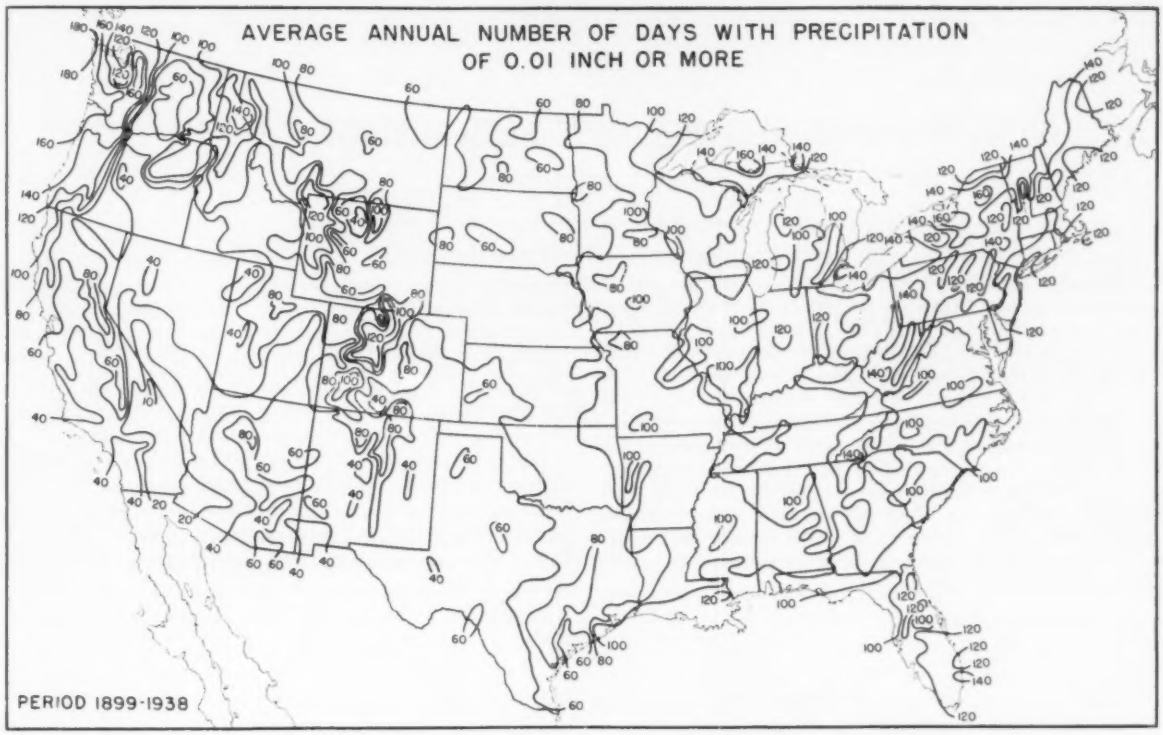

FIGURE 5.—Average annual number of days with precipitation of 0.01 inch or more, 1899–1938. (From [10].)

that he can calculate the probable job duration and the probable cost of idle equipment. If it would take 0.25 inch or more to halt his operations, then he should have available precipitation statistics based on that threshold value. If his operations were not planned to last a year, he would need similar statistics based on monthly or seasonal data. Therefore, monthly and annual charts of higher threshold values are needed.

Preliminary work by the writer indicates that the normal distribution should hold for higher thresholds up to at least 1.00 inch for annual as well as monthly precipitation data. At some point beyond 1.00 inch, it seems likely that the threshold occurrences, particularly monthly, begin to fall into the rare event class and will require different treatment. Investigation is continuing on this point.

ACKNOWLEDGMENTS

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Weather Bureau Technical News

ELECTRONIC WEATHER MAP "PLOTTER"

An electronic computer-plotter that mechanically draws a complete weather map in less than three minutes was put into regular Weather Bureau service December 1, 1960, at the National Meteorological Center in Suitland, Md. The "weather plotter", which produces a completed Northern Hemisphere weather map about seven times faster than the former hand-drawing method, is an important step forward in the Weather Bureau's automation of weather data processing, weather analysis, and weather forecasting.

The electronic unit reads weather information supplied in numerical form on magnetic tape, presents the information to a digital-to-analog converter that in turn instructs a plotting board to draw automatically contours on a 30-by-30 inch map of the Northern Hemisphere. The plotter is equipped with a mechanical "hand" which guides an inked stylus on instruction from the analog impulses.

Information fed into the weather plotter is gathered from more than 500 weather stations throughout the Northern Hemisphere, fed into the NMC by teletypewriter, and automatically checked and converted into input data for the Bureau's IBM–7090 high-speed electronic computer. Forecasts, ranging from 12 to 24, 48, and 72 hours ahead, are produced with the computer and recorded on magnetic tape. The tape is then "fed" into the weather plotter for reading, conversion, and drawing of the contours.

During the course of a 24-hour day, 64 weather maps are produced by numerical methods for various altitudes from sea level to 40,000 ft. Each map forecasts air flow patterns for a particular forecast period. The maps are distributed by facsimile throughout the United States for use in local and regional weather forecasting.

NEW WEATHER FACSIMILE NETWORK

A new high-speed National Weather Facsimile Network, operated by the Weather Bureau over lines leased from Western Union, was established in December 1960. Transmission of weather maps is twice as fast over the new circuit as over the one formerly in use. Thirty-five Northern Hemisphere upper air analyses and forecasts prepared with the aid of the Bureau's electronic computer and drawn by the new electronic weather plotter represent about one-third of all regularly scheduled charts prepared and transmitted by the National Meteorological Center at Suitland, Md. Several weather maps will be prepared and transmitted by the Weather Bureau's Severe Local Storm Center in Kansas City, Mo. Time has also been reserved in the 24-hour facsimile schedule for the transmission of cloud analyses based on photographs taken by the TIROS II weather satellite. Every 24 hours, more than 100 weather maps are sent over the new facsimile network to about 650 government, military, commercial, and private receiving stations in the contiguous United States and southern Canada.

A STUDY OF THE EFFECT OF TREE LEAVES ON WIND MOVEMENT*

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ABSTRACT

Using wind data observed in the micro-meteorological portion of the Nashville Community Air Pollution Network, a study is made of wind flow near deciduous trees during periods of foliation and defoliation. This difference in wind flow is contrasted with wind patterns in treeless or nearly treeless environments. It is concluded that in an area of numerous but well-spaced mature deciduous trees, the wind is about 25–40 percent greater during periods of defoliation.

1. INTRODUCTION

Trees have been used for protection from the wind for ages past. Numerous quantitative measurements of this protection have been calculated by use of speed measurements on the windward and lee sides of windbreaks. Little attention, however, has been paid to what portion of this measure of protection is due to leaves on deciduous trees. This study attempts to develop a measure of the contrast of wind speeds through deciduous trees during periods of foliation and defoliation.

The U.S. Public Health Service operated a network of air sampling stations in Nashville, Tenn., during the period from August 1, 1958, to July 31, 1959 [1]. This network consisted of 119 stations in the urban area and four rural control stations. The urban stations were located by a grid pattern centered roughly on a point just behind the Federal Building in downtown Nashville. A rural control station was located in each of the cardinal compass points approximately 8 miles from the center station of the grid. In addition to the various air sampling instruments located at each of the stations, 32 of the urban stations were equipped with anemometer/odometer instruments to record 24-hour wind movement. The anemometers were mounted on utility poles between 30 and 35 feet above ground. These 32 wind observing sites were randomly selected to approximate a grid-within-a-grid pattern (fig. 1) and consequently represented a sampling of various environmental factors. The random sampling process so desirable in this type of survey naturally resulted in some anemometers being placed in wooded sections of town with a small number of instruments located within a few hundred feet of numerous trees. A study of wind movement by seasons at these "tree-influenced" stations contrasted with wind movement at other stations in the network presents an opportunity to evaluate the effect of tree leaves on wind.

*This work was sponsored by the Public Health Service, U.S. Department of Health, Education, and Welfare.

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2. METHOD OF ANALYSIS

Monthly averages of 24-hour wind movement were computed for each station and month for which reasonably complete data are available. These monthly average station values were then combined to yield a monthly average 24-hour wind movement for the network (fig. 2). As would be expected, monthly average wind speed during the colder months of the year is greater than during the warmer months for the network as a whole. This increase is about 34 miles per day between October and November and corresponds with the normal climatological expectancy [2] which shows an increase in average hourly wind speed from 5.2 m.p.h. in October to 7.7 m.p.h. in November.

A ratio of station monthly average speed to network monthly average speed and to Weather Bureau Airport Station (WBAS) monthly average speed was computed for each station-month. Results of the two computations were quite similar due to the high correlation between network and airport wind observations. Since the WBAS winds are generally considered to be standard for the area, the ratio of station monthly average wind speed to WBAS monthly average wind speed, expressed as a percentage, has been adopted as the basis for this analysis. Hereafter, for sake of brevity, this ratio will be referred to as S/A—station to airport ratio. The computed values of S/A are tabulated in table 1.

Changes in S/A for individual successive months at a station are often difficult to explain and might be due to a great variety of influences. Therefore, an average S/A for homogeneous seasons was thought to be possibly more meaningful. Accordingly, an average S/A for the 3-month period of August, September, and October was calculated to represent the period when deciduous trees are foliated and will be referred to as $(S/A)_{summer}$. The December, January, and February average was selected to represent the period of defoliation and will be referred to as $(S/A)_{Winter}$. This selection of months is based on

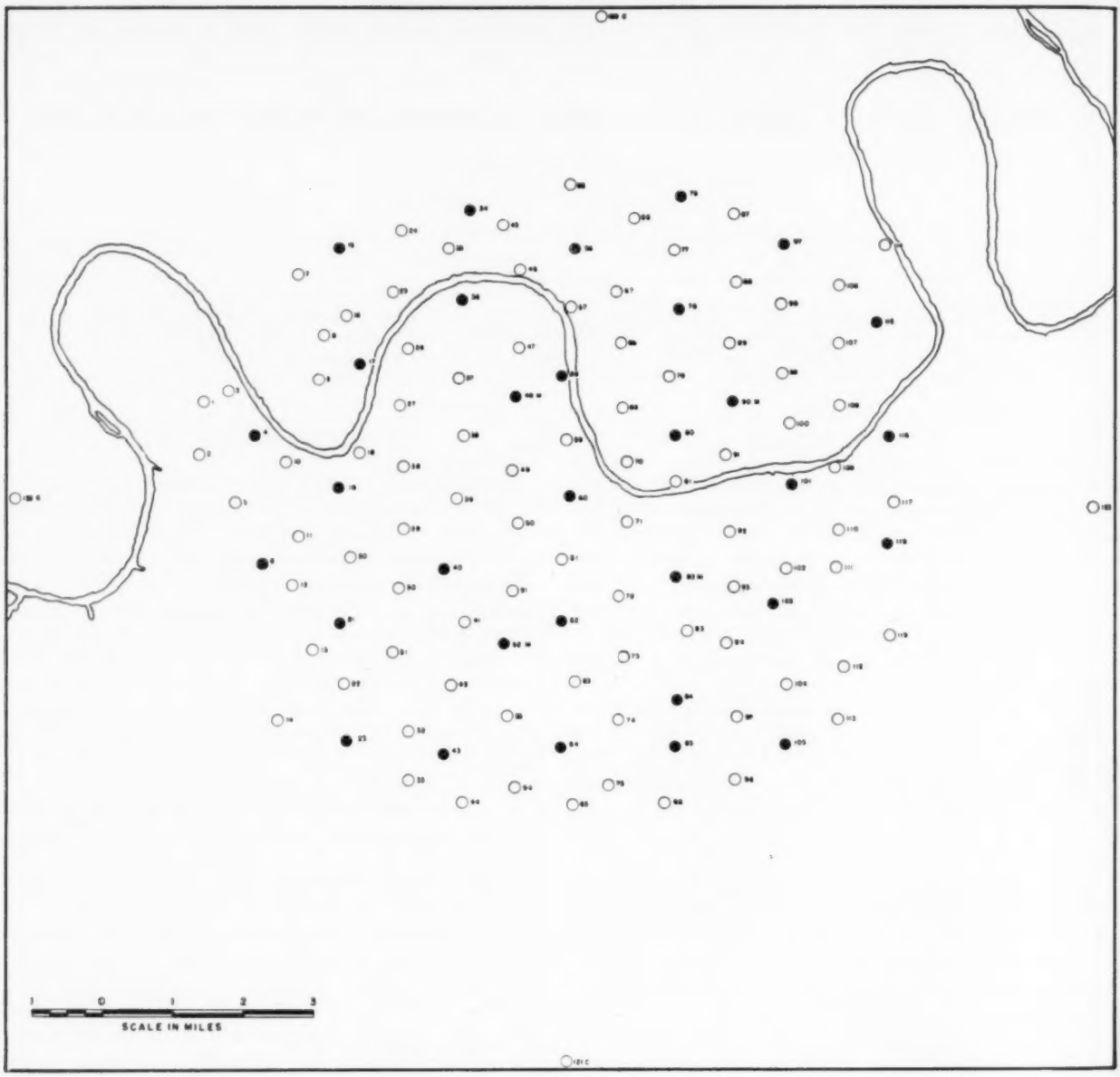

FIGURE 1.—Sampling station network, Nashville Community Air Pollution Study. Solid circles show anemometer/odometer sites.

information obtained by Dickson [3] from the Tennessee Division of Forestry which advised that defoliation in the vicinity of Nashville begins at or before the time of the first fall freeze (normally November 7 at Nashville) with most of the leaves down by about mid-November. Leaf emergence normally begins in early March but is highly variable depending upon the weather. Thus the months selected contain little or no transition period and should truly represent the physical qualities selected for study.

A second ratio has been formed for each station. This will be referred to as W/S and is formed by dividing $100 \times (S/A)_{Winter}$ by $(S/A)_{Summer}$. Table 2 lists, for the 30 stations that have acceptable records for the period studied, the following: Average 24-hour wind movement, August-October (col. 1) and December-February (col. 2); average ratio $(S/A)_{Summer}$ (col. 3); average ratio $(S/A)_{Winter}$ (col. 4); ratio W/S (col. 5).

In all cases the ratio W/S is greater than 100 indicating that $(S/A)_{Winter}$ is always higher than $(S/A)_{Summer}$. One reason for this is the character of the instruments being compared. The WBAS anemometer is more sen-

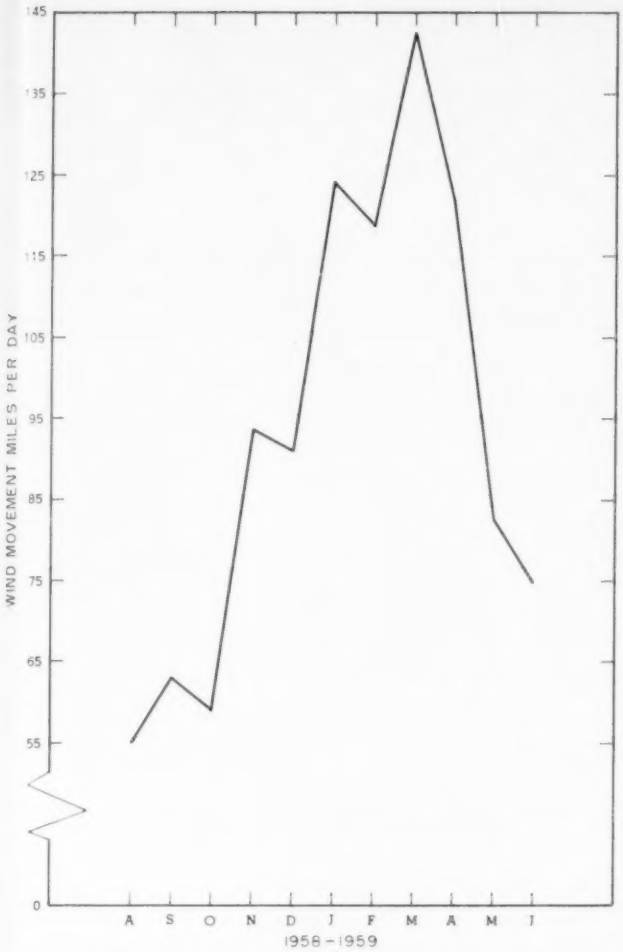

FIGURE 2.—Monthly average 24-hour wind movement at stations of Nashville Community Air Pollution Network, August 1958 through June 1959.

sitive and has a lower starting speed than the survey instruments. Thus in summer, with its greater proportion of light winds, the survey instruments measure a smaller percentage of actual winds than they do in winter. A second reason is that the stronger winds are less stable and have greater ability to penetrate the jungle of buildings that make up an urban area and thus bring wind measurements in this urban complex into better agreement with the well-exposed and relatively open airport location. Those arguments not only explain the increase of S/A in winter but also explain the fact that WBAS daily winds are consistently higher than those measured by the survey network.

It would be more conclusive to this study for data following spring emergence likewise to be contrasted with the winter data. Unfortunately much data were lost after February because of an increasing frequency of equipment failure. Three of the test stations are missing

TABLE 1.—*Monthly average values of S/A for stations in the Nashville Community Air Pollution Wind Network, August 1958–June 1959*

Station No.	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June
4	48.5	50.1	52.6	55.1	58.7	62.9	62.5	65.5	55.0		52.0
15	56.6	61.6	59.7	60.1	55.8	62.1	67.2		66.3	61.4	58.2
17	48.3	45.0	50.2	57.8	52.6	61.5	59.5	70.0	62.7	52.7	51.5
19	57.7	60.5	60.8	64.3	59.8	66.8	67.9	73.3	67.6	60.5	58.9
21	22.8	26.0	24.8	37.2	35.0	39.6	39.4				
23	36.5	40.7	37.3	52.5	52.6	56.1	57.5	58.0	52.7	45.7	43.8
34	48.3	47.6	49.1	52.0	51.8	57.1	57.3				
36	51.2	54.3	52.7	57.7	49.8	59.8	60.6	69.6	64.8	58.7	57.9
40	23.8	24.3	23.9	26.5	31.1	33.9	33.8	32.5	29.1	26.5	23.5
43	43.6	46.9	42.5	54.3	50.6	55.4	60.8	66.7	60.7	55.6	
48	44.4	45.1	41.7	41.7	46.3	46.6	47.7	48.3	44.3	42.2	
52	54.4	55.4	59.5	56.6	57.4	56.1	56.8	57.2	54.5	52.4	52.2
56	48.4	55.1	54.5	55.2	54.7	57.1	57.6	65.0	49.1		
58	46.3	46.6	43.7	46.5	43.3	51.9	54.5	59.9	56.6	56.4	54.8
62	29.9	26.7	30.8	34.2	39.0	38.2	37.9	39.2	33.3	26.4	26.0
64	36.9	35.0	33.3	49.4	51.4	54.9	57.6	57.7	52.9	41.6	
76	45.8	50.1	45.5	49.8	48.4	52.8	58.1				
78	29.9	32.0	33.7	36.0	37.3	41.0	44.4	47.5	44.3	31.9	31.5
80	31.2	34.7	32.4	35.1	37.9	38.4	40.8	45.3	39.2	34.1	40.2
82	53.7	55.2	63.0	65.8	63.7	68.5	70.2	68.5	67.8	56.3	52.6
84	51.9	54.4	52.9	61.1	59.6	69.4	69.0	70.4	61.3	54.4	52.2
85	63.6	69.1	63.0	69.4	67.4	77.6	77.6	78.4	75.7	76.1	69.7
90	32.8	33.1	36.1	36.6	38.9	39.1	43.3	46.0	43.6	34.0	32.3
97	23.2	20.5	27.9	32.9	35.6	36.0	39.4	39.7	33.9	22.7	25.4
101	25.5	25.1	23.9	32.3	31.0	36.0	37.1	37.7	34.3	24.8	20.6
103	50.2	55.2	53.3	59.2	55.9	62.9	65.2	68.4	66.9	56.0	55.6
105	42.0	40.2	51.5	61.8	59.0	63.6	70.4	67.5			51.7
115	40.4	36.5	43.3	52.2	54.7	59.6	61.7	62.0	59.4	47.6	42.8
116	51.9	60.7	56.1	64.0	61.3	66.6	66.1	72.4	67.9	63.9	60.8
118	48.6	49.4	51.9	53.7	59.9	61.4	66.1	63.6	57.5	42.7	41.9

TABLE 2.—*Average 24-hour wind movement $\overline{V}$, average ratio S/A, and ratio W/S at stations of Nashville Community Air Pollution Wind Network*

Station No.	(1) $\overline{V}$ (Aug.–Oct.)	(2) $\overline{V}$ (Dec.–Feb.)	(3) $(S/A)_{summer}$ (Aug.–Oct.)	(4) $(S/A)_{winter}$ (Dec.–Feb.)	(5) W/S $\left(\frac{100 \text{ col. } 4}{\text{col. } 3}\right)$
4	67.4	127.5	50.4	61.4	122
15	79.3	128.3	59.3	61.7	104
17	63.8	120.7	47.8	57.9	121
19	79.8	134.9	59.7	64.8	109
21	32.8	79.2	24.5	38.0	155
23	51.1	115.1	38.2	55.4	145
34	64.8	115.3	48.3	55.4	115
36	70.5	118.4	52.7	56.7	108
40	32.1	68.5	24.0	32.9	137
43	59.3	115.7	44.3	55.6	126
48	58.4	97.1	43.7	46.9	107
52	75.4	117.6	56.4	56.8	101
56	70.5	117.2	52.7	56.5	107
58	60.9	104.1	45.5	49.9	110
62	38.8	79.4	29.1	38.4	132
64	46.8	113.5	35.1	54.6	156
76	63.0	110.5	47.1	53.1	113
78	42.6	85.1	31.9	40.9	128
80	42.9	81.0	32.8	39.0	119
82	76.5	140.2	57.3	67.5	118
84	71.0	137.6	53.1	66.0	124
85	87.3	154.6	65.2	74.2	114
90	45.4	83.9	34.0	40.4	119
97	31.8	76.7	23.9	37.0	155
101	33.2	72.3	24.8	34.7	140
103	70.8	127.7	52.9	61.3	116
105	59.4	133.8	44.6	64.3	144
115	53.4	122.0	40.1	58.7	146
116	75.4	134.4	56.2	64.7	115
118	66.7	129.6	50.0	62.5	125
Mean	59.04	111.4			

or incomplete following February. The results at the remaining stations are generally as expected but the distinction between "tree-influenced" and other stations is not so clear-cut as during the fall period of defoliation. This is thought to be because the emergence of the leaves and their growth to maturity is a more gradual process

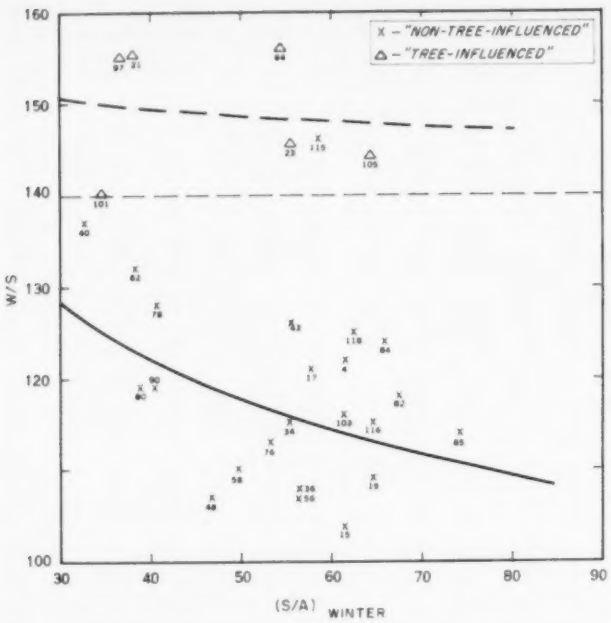

FIGURE 3.—Scatter diagram of W/S vs $(S/A)_{Winter}$. The solid line is fitted to values for the "non-tree-influenced" stations and the heavy dashed line to values for the "tree-influenced" stations.

than is the defoliation process of fall. In discussing individual stations, the spring data are presented where available.

3. STUDY OF DATA

It will be noted in table 2 and figure 3 that there are seven network stations which show W/S values of 140 or higher. A study [4] of the environment of these stations shows that six are influenced by trees within a radius of a few hundred feet. These six stations have been labeled "tree-influenced" since no other physical reason can be found for their significantly higher W/S. Additional inspection shows that other stations having W/S above network average (122.3) but below 140 also have some trees in the vicinity but the narrative descriptions of the stations indicate that the trees are at greater distances, lower heights, and/or more widely scattered than at the so-called "tree-influenced" stations.

A mean $\overline{W/S}$ for the "tree-influenced" stations was formed and a second mean $\overline{W/S}$ was formed for the remaining stations (those considered non-tree-influenced). Through the use of an F variance ratio test and a t test, it was statistically shown that the two means do not, at the 0.95 confidence level, come from the same population. Since tree influence was the determining characteristic, with no consideration given to geographic location, topographic exposure, or other factors in selecting the two groupings of stations (making up the mean $\overline{W/S}$), it is suggested that the factor leading to the measured population difference in $\overline{W/S}$ is the presence or absence of trees in the immediate vicinity of the reporting stations.

It was mentioned that seven stations report W/S of 140 or higher but only six are considered "tree-influenced." No such influence can be found at the seventh (115). Station 115 is located in a new residential area with only scattered trees, few of which are as high as the instrument. It is possible that the increase (or part of it) is due to the terrain which slopes away from the site in the north and west directions with a slight rise toward the east and south. Thus, while the station is protected from the prevailing southerly winds of the warmer seasons, it is not protected from the more frequent and stronger westerly and northerly winds of winter. An alternate explanation that appears possible is that, in this area of new housing, land clearing activity in the fall may have altered the wind pattern.

Figure 3 is a scatter diagram of a part-whole correlation* with $(S/A)_{Winter}$ as abscissa and (W/S) ratio as ordinate. The diagram shows that the increased S/A in winter is greater at stations with lower average speed and this does not appear to be a linear function. The top (dashed) regression line is empirically fitted to the data from the six "tree-influenced" stations. The lower (solid) regression line is fitted to the 23 "non-tree-influenced" stations. The interesting feature of the diagram is how clearly the "tree-influenced" stations stand apart from the remainder of the network to illustrate that some influence is present at these particular stations which causes their winter S/A to increase to a far greater extent than the remainder of the data would lead us to expect. Once again it is suggested that this influence is the presence of deciduous trees.

4. DISCUSSIONS OF INDIVIDUAL "TREE-INFLUENCED" STATIONS

Site 21.—The anemometer is in an older residential neighborhood located in a shallow valley. There is a gentle rise toward all directions but the southwest. The area is wooded with trees in most directions, at various heights and distances, and there are few openings in the tree barrier. Some 35- to 40-ft. trees are within 100 ft. of the anemometer to the northeast and east. Within a 300-ft. circle there are trees of 50 ft. or higher. The greatest concentration of trees appears to be to the west of the instrument. The W/S ratio at this station was 155. The acceptable record for this station ended in February so no conclusions can be made about the period after spring foliation.

Site 23.—The anemometer is in a well-established residential neighborhood (fig. 4). The environment is heavy with trees and vegetation. This part of town is a series of rises, knolls, and small hills. The anemometer site is on top of one such rise. Most of the trees within 100 ft. of the instrument appear lower than the exposure height but many higher trees are situated between 100 and 300 ft. distant. The W/S ratio at this station was 145. During

*The term plotted as abscissa also appears as a portion of the ordinate term. In other words $(S/A)_{Winter}$ appears in both ordinate and abscissa and thus the diagram contrasts one variable with itself plus an arithmetic combination of itself and some other term.

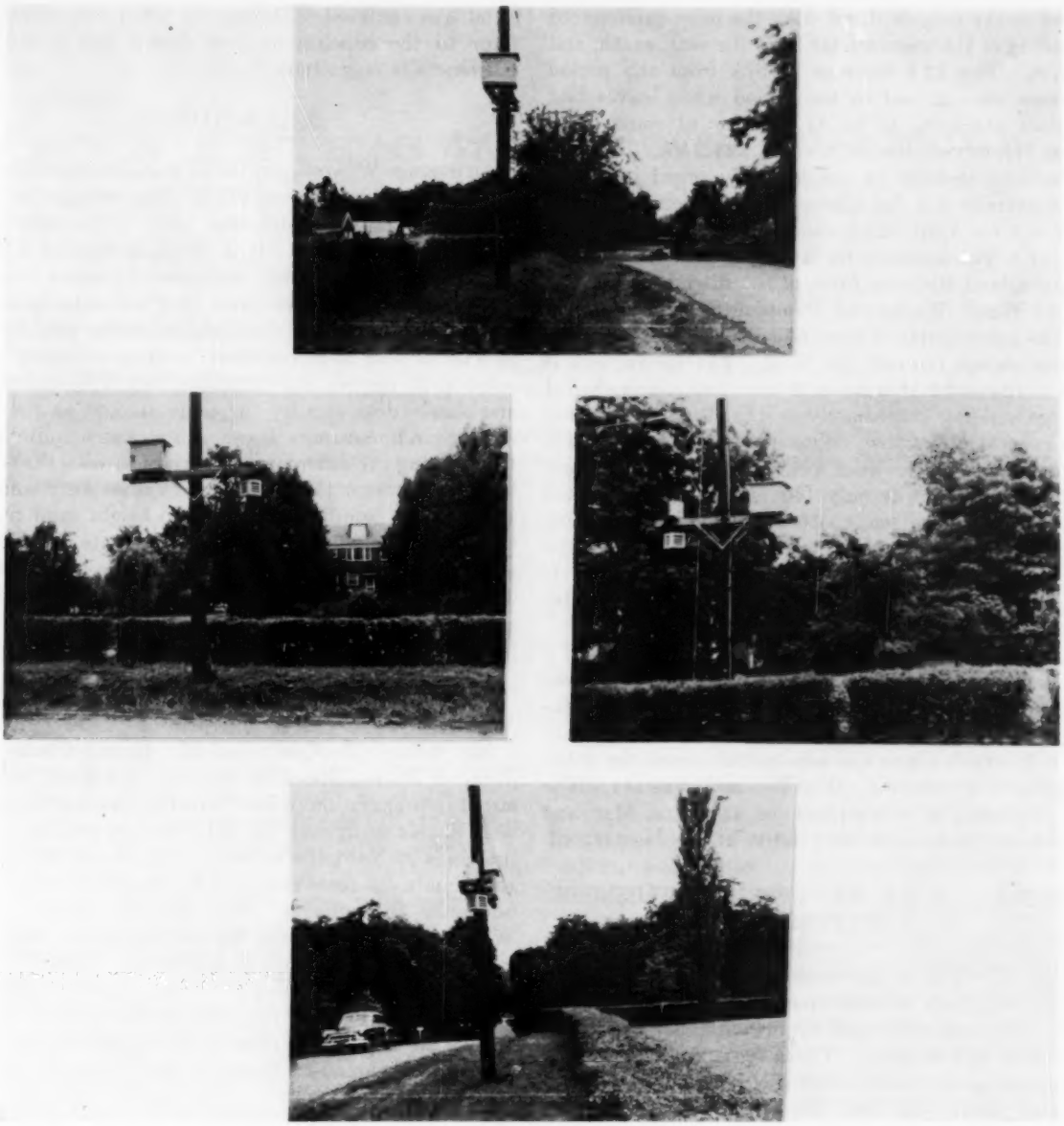

FIGURE 4.—Site 23, a typical "tree-influenced" station. Anemometer is located atop the utility pole. Starting at top and moving clockwise pictures are taken looking north, east, south, and west on May 30, 1959.

the spring period of leaf emergence the S/A ratio winter to spring was 117. The S/A ratio between winter and spring would not usually be as large as the ratio between winter and late summer-early fall because of the higher wind speeds in spring (as opposed to fall). The 117 value for this station was exceeded by a few "non-tree-influenced" stations, but due to unreliability of much of the spring data this is not accepted as disproving the theory here investigated.

Site 64.—The anemometer is situated in a residential neighborhood composed mostly of ranch type houses. The location is close to the top of a knoll with the greatest down-slope toward the west. There are trees higher than the anemometer about 200 ft. to south-southwest while the east is blocked by trees 300 to 500 ft. away. The S/A increase after leaf fall at this observation point was 19.5 or a W/S ratio of 156. The spring data are incomplete but the record available indicates a trend consistent with the postulation.

Site 97.—A residential neighborhood surrounds this station. The whole section of town is relatively low but in the immediate vicinity of the site there is a gentle down-slope toward the east with a somewhat sharper down-slope starting a short way to the north. There are numer-

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ous trees in the neighborhood with the most pronounced tree-shading of the anemometer from the east, south, and northwest. The 13.1 increase in S/A from the period when trees were in leaf to the period when leaves had fallen does not seem to be as great as at some other stations. However, the W/S ratio was 155. The S/A ratio declined steadily as the leaves emerged in spring and the average S/A for winter was 136 percent of the average S/A for April, May, and June.

Site 101.—The anemometer is located near the bank of the Cumberland River in front of the filter house at the Nashville Water Works and Pumping Station. This is one of the lowest parts of town and the terrain rises in all directions except toward the river. The instrument is located in the midst of a group of trees and is also shaded by a large building immediately to its south and by rising terrain in most directions. With all these obstructions it is, of course, one of the least windy exposures. The fact that the W/S ratio was only 140 is probably explained by the fact that the many other obstructions diminish the wind before the trees can affect it. The S/A ratio in the spring declined steadily as the leaves emerged and developed and the winter S/A divided by the average from April through June was 130.

Site 105.—The anemometer is located near the top of a hill in a residential neighborhood. There are a number of trees in the vicinity with the highest trees in the southwest and west and also in the eastern quadrant. A study of the S/A reveals about the same pattern as at the other "tree-influenced" stations. The W/S ratio was 144. The record is missing at this station for April and May and there is some question of the validity of the June record.

5. EXAMPLES OF S/A AT "NON-TREE-INFLUENCED" STATIONS

Station 36.—This is an excellent example of an anemometer completely without tree influence in its vicinity. This site is located on a small airport with only a few trees some 600 ft. to the north. The August, September, and October average S/A contrasted with average S/A during the winter months was 108. Site 36 showed a rise of S/A in the spring and finally reached a ratio higher than its fall value.

Station 85.—The anemometer is located in a light industrial area of well-spaced one-story office and warehouse buildings (all lower than the instrument). There are no trees close to the site. Here the ratio rose 9 units during the winter yet the ratio between winter and late summer-early fall was only 114.

Stations 19 and 56.—Both stations had an S/A increase of about 5 units and ratio of less than 110. Once again narrative descriptions of each station make note of the lack of tree influence.

The pattern was generally consistent with low W/S ratios at well-exposed locations and higher values at stations in and near trees. At times, however, the spring trend was confused. This spring trend was seldom contrary to the conclusions here drawn but it did show differences in magnitude.

6. CONCLUSION

An average W/S ratio for the 23 stations considered to be "non-tree-influenced" was 122.3. The average for the six "tree-influenced" stations was 149.2. The difference is statistically significant. It is therefore concluded that in an area of numerous but well-spaced mature deciduous trees or clumps of trees (such as a well-established residential neighborhood), after defoliation the wind increases by a factor near 25 percent over "average exposure" and as much as 40 percent over exposures nearly devoid of trees, and slowly decreases by the same amount as the leaves emerge and mature. These values agree quite closely (considering the differences in variables) with those found by M. Toperczer [5] in Vienna. Values vary somewhat according to number of trees, tree height, and tree distances. It is suggested that an approximate mathematical expression of leaf effect upon wind movement could be developed. However, this would require a specially designed network with accurately measured variables (tree height, density, and distances).

ACKNOWLEDGMENTS

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DESCRIPTION OF THE 50-MB. PATTERNS OVER ANTARCTICA IN 1958

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ABSTRACT

Seasonal variations in the 50-mb. circulation over the Antarctic during 1958 are discussed and the features observed in 1957 are compared with those found in 1958. Both years exhibited similar patterns in the fall and winter seasons but differed somewhat in spring and summer. In 1957, the polar vortex of winter began to weaken in early October and by November 21 a closed anticyclone at 50 mb. encompassed the continent. In 1958, the breakdown of the polar vortex was more gradual and by the end of November the 50-mb. circulation was characterized by an irregular pattern of closed cyclones and anticyclones rather than a dominant anticyclone.

1. INTRODUCTION

Although it is too soon to receive the full amount of checked data from the Antarctic stations participating in the IGY program, it is felt that a sufficient number of reports are available from the radio broadcasts in 1958 to permit a preliminary analysis of the 50-mb. level over the continent (fig. 1).

The present work is more or less a continuation of the series of daily 50-mb. charts prepared by W. B. Moreland of the U.S. Weather Bureau during his tour of duty as chief of the Antarctic Weather Central at Little America in 1957. A comparison of the circulation patterns for the two years reveals some significant differences in the spring and early summer seasons. A more detailed discussion of these differences will be attempted later in this paper.

The series of charts for 1958 was plotted and analyzed at 10-day intervals with data for one day on either side of the 10th day added as an aid in analysis. These charts were based on 0000 GMT data, although 1200 GMT data were used as an aid in analysis. Extrapolations, by thickness techniques, from levels between 100 mb. and 50 mb. were carried out whenever practicable to obtain better coverage of the 50-mb. heights and temperatures. This method of analysis is similar to that employed by Austin and Krawitz [1] in their Northern Hemisphere study, and by Teweles and Finger [2] in their higher stratospheric analyses.

The area covered by the analysis is, of necessity, confined to the Antarctic Continent and adjacent waters, since 50-mb. data from the islands in the Southern Oceans are quite meager. The contours are drawn at 100-meter intervals and the isotherms for every 5° Celsius. The maps included in this paper are excerpts from the series for the whole year which will be checked and completed as the final data become available.

2. SUMMER 1957–1958

The 50-mb. chart for January 15, 1958 (fig. 2), is fairly representative of the summer pattern at the beginning of this year although the circulation had been predominantly anticyclonic from the middle to the end of December 1957. The flat contour gradient and relatively uniform temperatures over the entire continent persisted until early March 1958.

The Low centered at about 80° S., 100° E. apparently had moved into this region from the western coast of Queen Maud Land. It remained over East Antarctica but exhibited a variable intensity and occasional breakoff of secondary cells until the middle of March, when a single pronounced vortex and strong cyclonic circulation developed over the whole continent.

The ridges along the coastal areas fluctuated in shape and extent, sometimes forming separate small high cells over the continent. There appeared to be some general westward drift to these ridges during the summer.

The chart for February 5, 1958 (fig. 3), depicts the variations in the systems discussed above. The Low over the Ross Sea seems to have been a part of the larger system centered over East Antarctica. Rather prominent ridges appeared over the coast near D'Urville and over the Ellsworth Highland with the possibility of a small closed High in the latter area at about 74° S., 85° W. It should be recognized, however, that trying to maintain continuity of these factors on charts drawn for 10-day intervals may not be too satisfactory.

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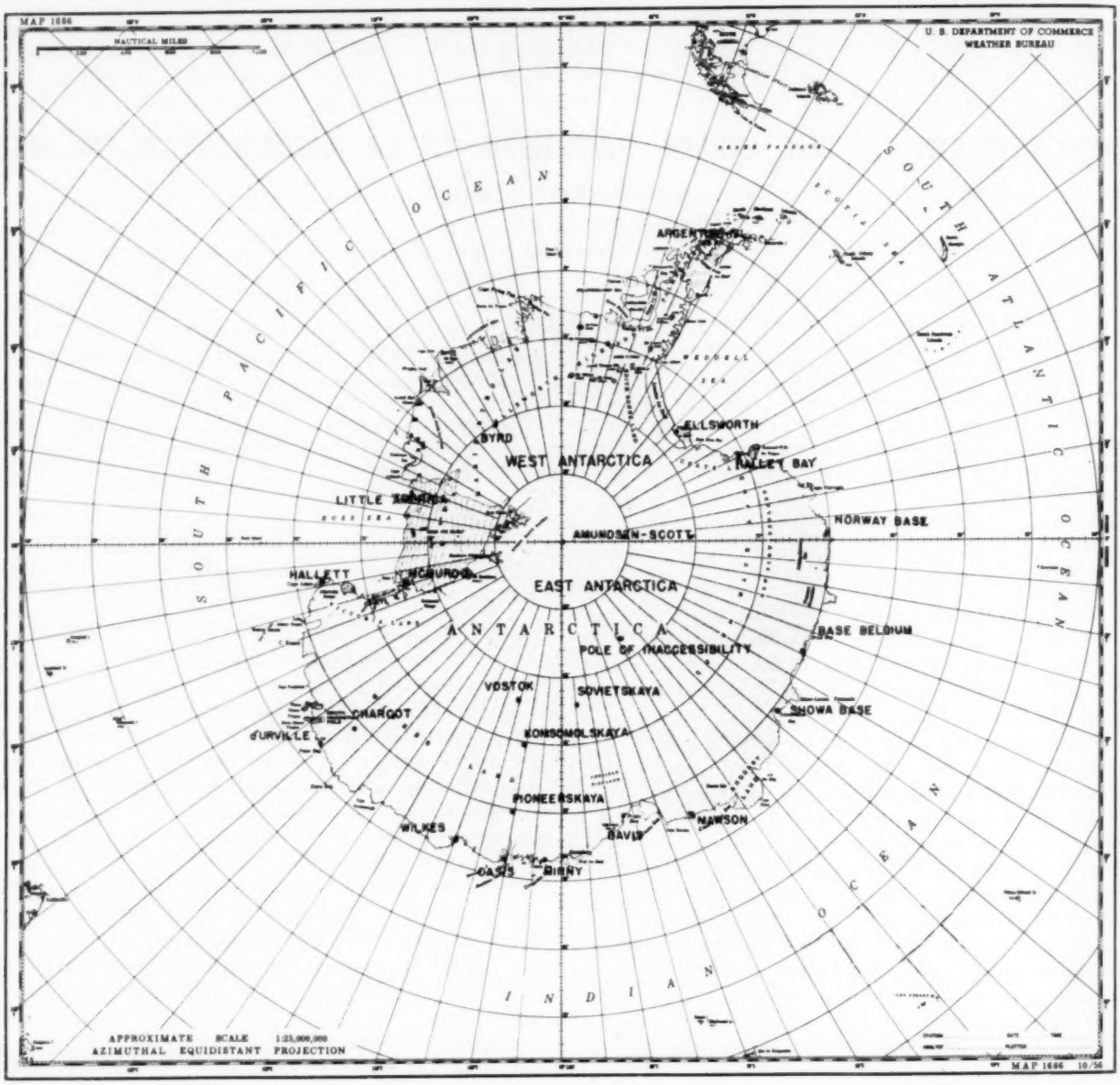

FIGURE 1.—Antarctica and stations established during the International Geophysical Year.

3. AUTUMN 1958

The transition from summer is first observed on the chart for March 15, 1958 (fig. 4). The development of this single prominent vortex appeared to be rather gradual. The first area to indicate a strengthening of the cyclonic circulation was the coastal region from D'Urville to Little America with winds of 30 to 40 kt. reported at stations in this part of the continent in the period March 14–16.

By April 15 (fig. 5), the circulation was stronger over the coast of the entire continent and the band of highest winds (40 to 50 kt.) extended from Mirny to Little America. The center of the circulation at about 85° S., 40° W. had a tendency to drift about the geographic pole in a general west to east direction but was most often located between the South Pole and the Weddell Sea and between the South Pole and the Pole of Relative Inaccessibility (82° S., 59° E.) during the year.

The large-scale features which developed by the middle of April were retained without much change throughout the fall season.

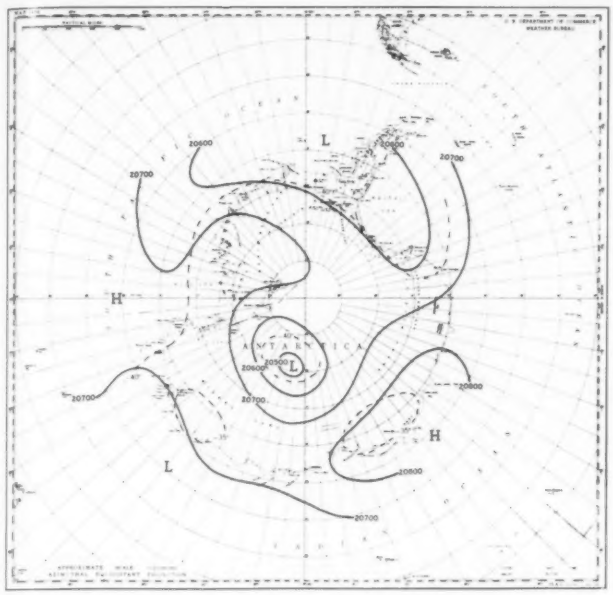

FIGURE 2.—50-mb. chart, January 14-16, 1958.

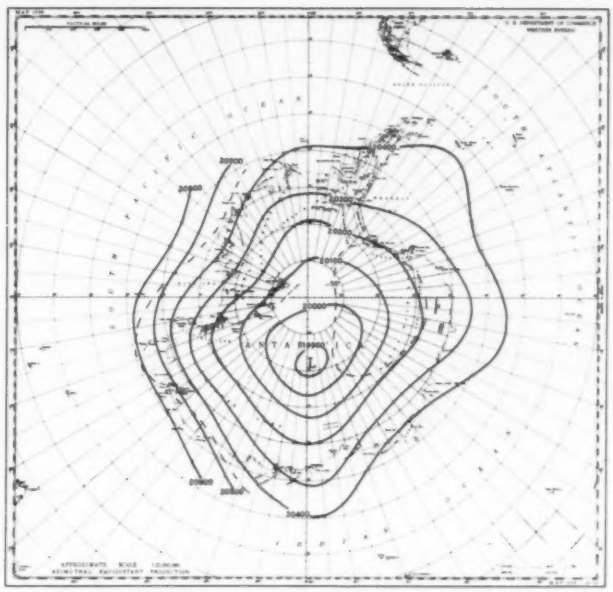

FIGURE 4.—50-mb. chart, March 14–16, 1958.

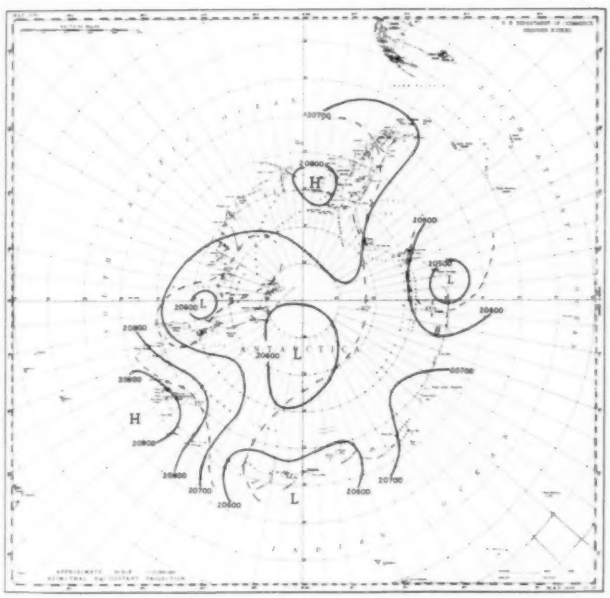

FIGURE 3.—50-mb. chart, February 4-6, 1958.

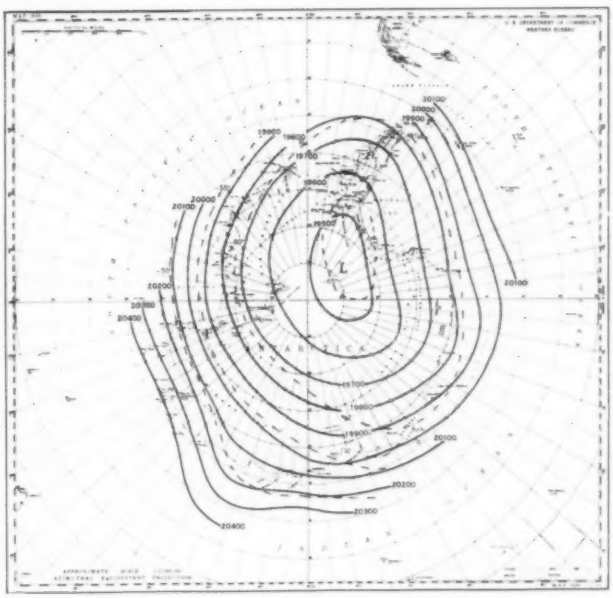

FIGURE 5.—50-mb. chart, April 14–16, 1958.

Cooling at 50 mb. over the continent was most pronounced over the Weddell Sea sector, but the decrease in all regions was fairly smooth.

4. WINTER 1958

A pattern typical of this winter season is shown on the chart for July 15, 1958 (fig. 6). It is characterized by a single center near the South Pole and strong zonal circulation with a weak three-wave pattern over the continent. At times during this month winds over Mirny and McMurdo reached speeds of over 100 kt. at 50 mb. Although the circulation had intensified over the coast of the entire continent it appears that the coasts of Wilkes Land and Victoria Land had consistently stronger winds during late fall, winter, and early spring. This may be attributed to the temperature contrasts resulting from the

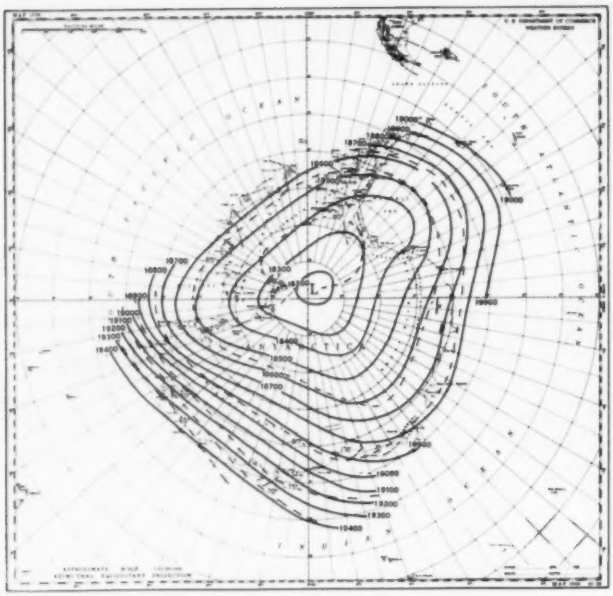

FIGURE 6.—50-mb. chart, July 14–16, 1958.

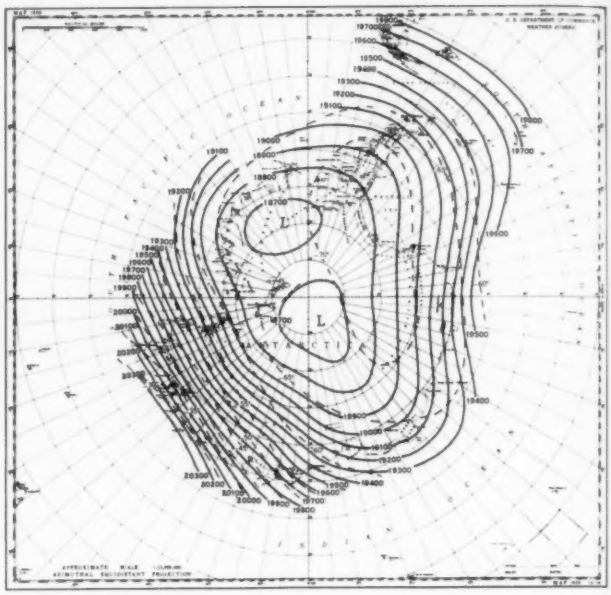

FIGURE 8.—50 mb. chart, October 14–16, 1958.

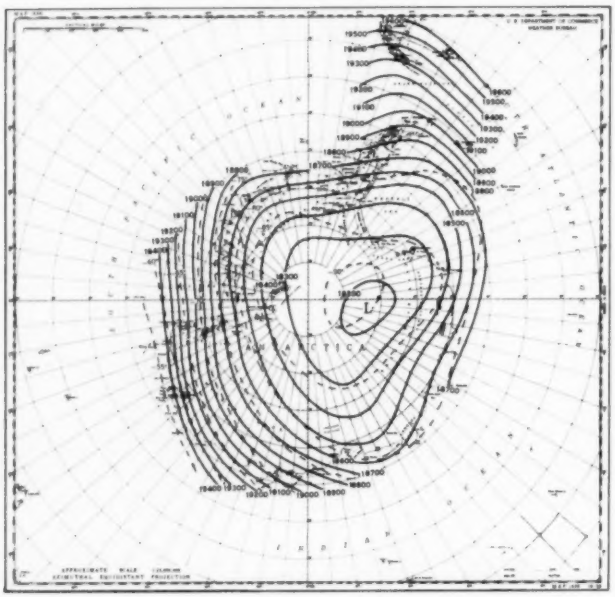

FIGURE 7.—50-mb. chart, August 14–16, 1958.

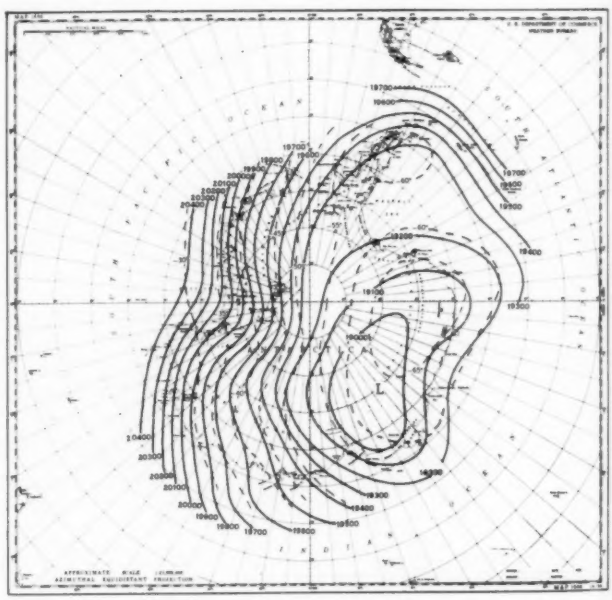

FIGURE 9.—50-mb. chart, October 24–26, 1958.

fact that the boundary of the polar night zone at 50 mb. was about 68° to 69° S. Unfortunately, no wind reports for this level are available at comparable latitudes on the Palmer Peninsula to check the validity of this hypothesis.

The three-wave pattern shown on this chart seems to be a representative feature of the maps for July and August 1958, whereas the maps for the spring and fall seasons indicate that four, and occasionally five, major troughs were more common.

By the middle of July the temperatures over the interior were between −85° C. and − 90° C., while the temperatures over the coastal areas ranged from −81° C. at the Belgian station, on the Atlantic side of the continent, to −65° C. at D'Urville, on the Pacific side. Again, it might be noted that while the isotherms did not exactly

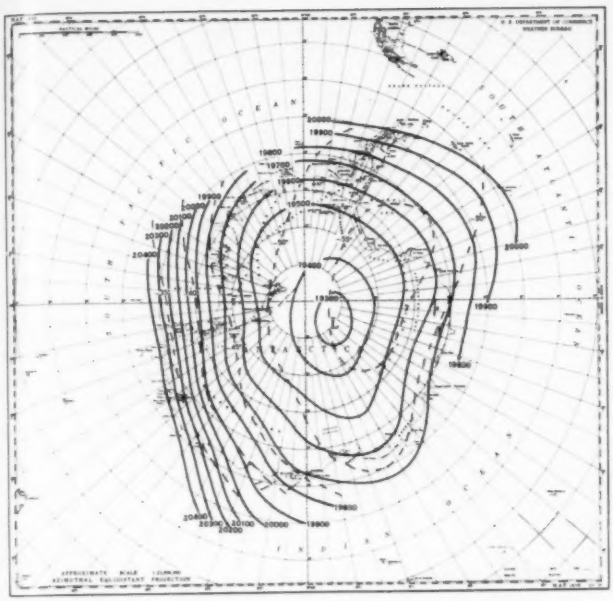

FIGURE 10.—50-mb. chart, November 4–6, 1958.

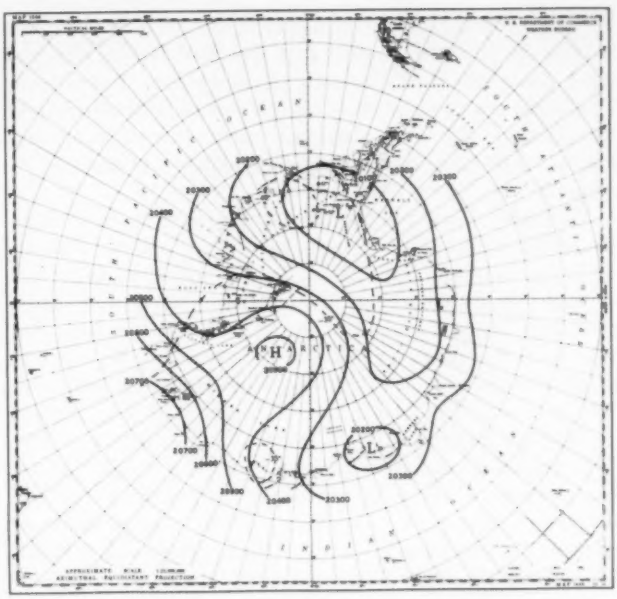

FIGURE 12.—50-mb. chart, November 27, 1958.

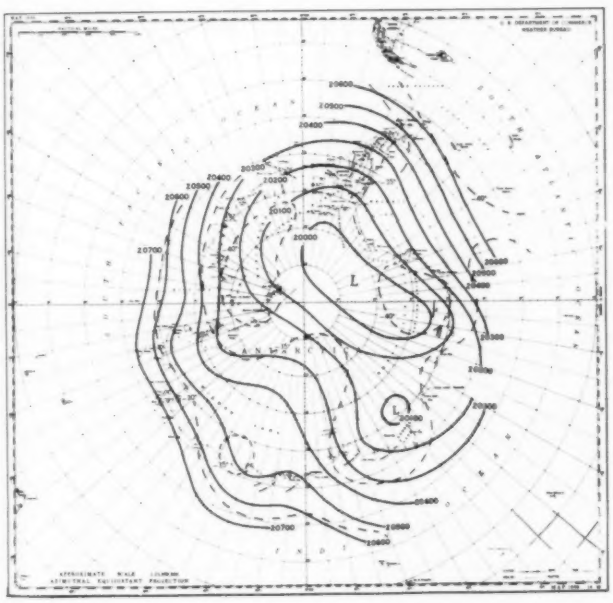

FIGURE 11.—50-mb. chart, November 24–26, 1958.

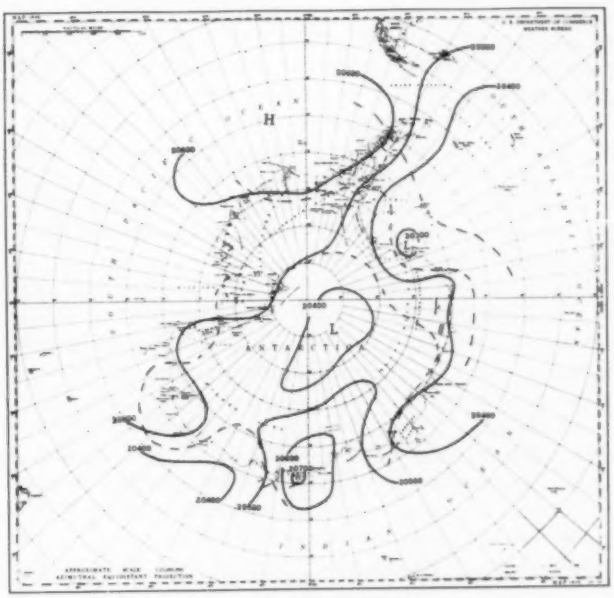

FIGURE 13.—50-mb. chart, December 4–6, 1958.

parallel the contours there was only a slight cross-contour orientation and, therefore, very little advective temperature change in the winter months.

The chart for August 15, 1958 (fig. 7), shows rather well-defined jets on opposite sides of the continent with winds of 50 to 60 kt. over the coast of Queen Maud Land and winds over 100 kt. (at 67 mb.) at D'Urville on the 16th. On the 14th McMurdo reported a wind of 145 kt. at 50 mb.

Although the band of strong winds over the coasts of the continent varied in intensity and lateral extent during the winter months, the winds over the coast of Wilkes Land and Victoria Land were rarely reported as less than 25 to 30 kt. at 50 mb.

5. SPRING 1958

It is in the spring season that the most radical changes take place in the Antarctic stratospheric circulation. The rapid warming at very high levels in 1958, described by Hanson [3], was also noticeable at 50 mb. and helped to produce the eventual breakdown of the winter cyclone.

The rate of warming at 50 mb. appears to have been about the same at both the coastal and interior stations in early October and this acted to maintain the band of high winds encircling the continent from the coast of Queen Maud Land to Wilkes Land and the Ross Sea shown on the chart for October 15, 1958 (fig. 8). Winds of 80 kt. were reported at the Norwegian station, over 100 kt. at Mirny and D'Urville, and 100 kt. at Hallett in the period October 14–16, 1958.

It might be noted in passing that the double center configuration of the polar vortex (fig. 8) was not a common occurrence although a similar pattern was evident on October 5, and once in each of May, June, and August.

On October 25, 1958 (fig. 9), the center of the polar vortex had shifted to about 75° S., 50° E. and a ridge had developed over the western Ross Sea and inland to near the South Pole. The band of high winds had moved inland over Wilkes Land and the Ross Ice Shelf. The apparent warm air advection and subsidence accompanying this change in circulation caused a rise in temperature to −37° C. at Wilkes and to −35° C. at McMurdo as contrasted with temperatures of −60° C. to −65° C. on the other side of the continent. The temperature at the South Pole rose from −68° C. to −53° C. in this 10-day period with a 6° increase taking place from the 24th to the 25th as a result of the change in circulation.

The relatively colder air associated with the polar vortex spread eastward and apparently acted to inhibit the warm air advection and help produce a breakdown of the developing ridge. The modification of the temperature gradient allowed a circumpolar flow to be re-established. The chart for November 5, 1958 (fig. 10), shows the center of the Low near 84° S., 40° E. with a circulation similar to the winter pattern. The temperatures had decreased somewhat over the coast of Wilkes Land and remained about the same over the Pole and coast of Queen Maud Land. The jet over Wilkes Land and the Ross Sea persisted until the 25th (fig. 11) when the pattern began to weaken and a ridge formed over East Antarctica.

A series of daily charts was analyzed from November 27 to December 1 to determine if a radical change in circulation occurred which might not have been detected in the usual 10-day map interval. This series showed that the ridge over East Antarctica continued to develop and there was a possibility of a closed High about 80° S., 125° E., while the Low was displaced to a position just south of the Palmer Peninsula with a trough extending over Queen Maud Land toward Mawson (fig. 12). These two features weakened gradually and appeared to move around the continent from west to east until a rather irregular pattern of isolated Lows and ridges was established by December 5, 1958 (fig. 13). This type of circulation was characteristic of the remainder of December 1958.

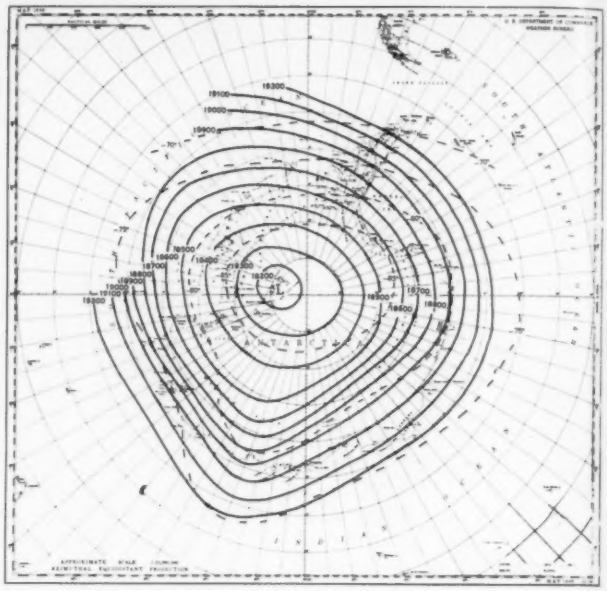

FIGURE 14.—50-mb. chart, July 15, 1957.

6. COMPARISON OF THE 50-MB. PATTERNS IN 1957 AND 1958

There is quite a bit of similarity between the 50-mb. charts of the fall and winter seasons of 1957 and 1958. The polar vortex over the continent developed rather gradually and was well established by the end of April of each year. A comparison of the charts for July of both years (fig. 6 and fig. 14) shows very little difference in the character of the winter circulation. It should be noted that differences in detail, such as the positions of troughs and ridges, occur on most of the charts for the two years.

It is in the spring and summer that a pronounced difference in the 50-mb. patterns is observed. In the first part of October 1957, a ridge developed over the coast of Wilkes Land and the major low center was displaced toward the Palmer Peninsula. The movement of these systems was accompanied by a shift of the jet across the South Pole with an orientation from about 20° E. to 160° W. long. By November 17, 1957 (fig. 15), the ridge was more firmly established over East Antarctica, and on November 21, 1957 (fig. 16), a closed anticyclone was centered about 78° S., 110° E. with easterly winds observed at all coastal stations. This pattern was substantially retained until January 1958.

In 1958 there was no major change in the winter type

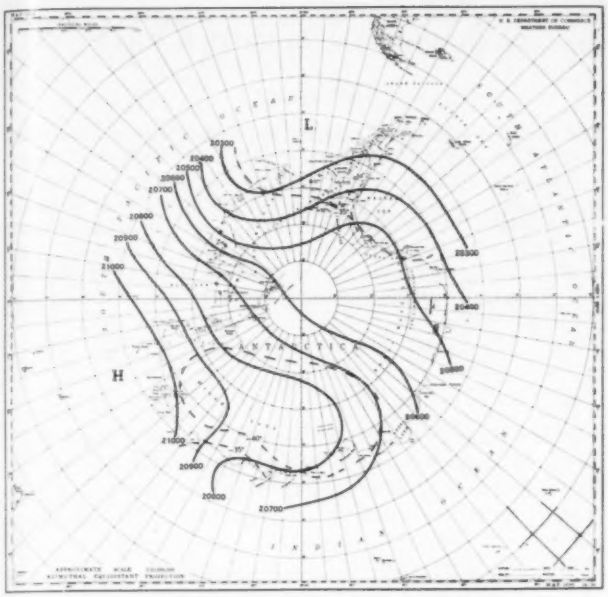

FIGURE 15.—50-mb. chart, November 17, 1957.

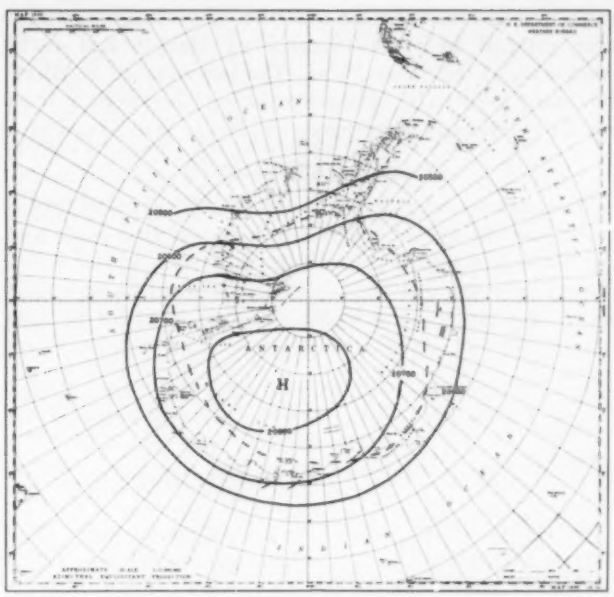

FIGURE 16.—50-mb. chart, November 21, 1957.

circulation until October 25, 1958 (fig. 9), when a ridge developed over the Ross Sea area and the jet was diverted across Wilkes Land directly toward Byrd Station. However, in this case, the low center was displaced to about 75° S., 50° E. as the major ridge built over the Ross Sea. The colder air associated with the Low apparently spread to the east inhibiting the continued development of the ridge. The consequent modification of the temperature gradient over Wilkes Land and the Ross Sea area helped to produce a more uniform circulation centered near 84° S., 40° E. (fig. 10).

The permanent breakdown of the pronounced circumpolar flow apparently was well-established by November 27 (fig. 12) with the build-up of a high cell over Wilkes Land at about 80° S., 125 °E., and the movement of the low center to just south of the Palmer Peninsula. By December 5, 1958 (fig. 13), as was noted before, the circulation pattern became rather unorganized and remained this way throughout the month.

The significant difference between the spring and summer patterns in the two years was that: (1) at no time in the spring and summer of 1958 did an anticyclone dominate the circulation over the entire continent as happened in 1957, and (2) the final breakdown of the strong polar vortex took place almost a month later in 1958 and at a more gradual rate than was observed in 1957.

As a point of interest in the comparison of the two years, a graph of the 50-mb. temperatures at three stations (South Pole, Mirny, and Hallett) was prepared (fig. 17). These temperatures, for both years, were plotted at 10-day intervals on the same basis as the maps for 1958.

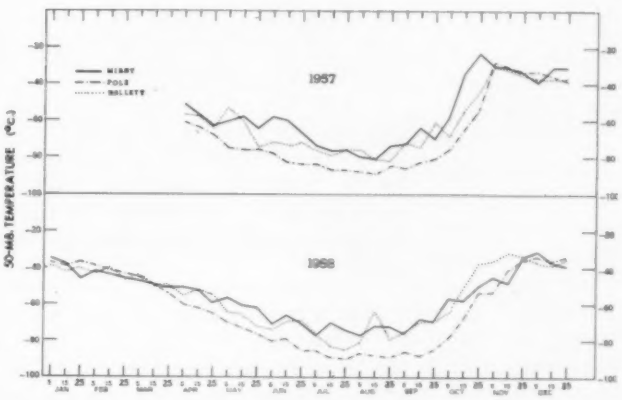

FIGURE 17.—50-mb. temperatures (° C.) at 10-day intervals, 1957 and 1958, at Mirny (solid line), South Pole (dashed-dotted line), and Hallett (dotted line).

Here again the two years were rather similar in the relatively gradual decrease of temperature beginning in the fall and continuing to a minimum reached in late July to mid-August. As was observed in the circulation patterns, a significant difference appeared in the temperatures for the spring and early summer seasons. In 1957, all three stations exhibited a sharp rise of temperature from the first of October with the maximum reached at Mirny about October 25 and at the South Pole and Hallett about November 5. From this point the temperature began falling slowly. In spring and early summer 1958 the temperature rose rapidly in October at the South Pole and Hallett but by about October 25 the increase had

stabilized and the warming was gradual until the maximum was reached in mid-November at Hallett and early December at the South Pole. The temperature at Mirny increased relatively gradually during this period to a maximum in early December.

ACKNOWLEDGMENTS

The authors are grateful to Mr. W. B. Moreland for his permission to use his analyses as a part of this paper and for his helpful suggestions during discussion of this work. Thanks are also due Mr. M. J. Rubin for his interest and aid in this project, and to Mr. W. S. Weyant for his help in preparing the final version of the paper. The 1958 series of charts was plotted by Mr. C. F. Fopay.

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New Weather Bureau Publication

The Cooperative Weather Observer, U.S. Weather Bureau, Washington, D.C., 1960, 116 pp. For sale by Superintendent of Documents, U.S. Government Printing Office, price 65 cents.

A booklet recognizing and honoring the voluntary services of the cooperative weather observers over the United States. It contains an explanation of early weather observational programs in the United States and the part played by the volunteer observers. Biographical sketches of observers with long service records are included and many examples of devotion to duty are cited. Institutions and organizations with long records of observations are also recognized.

THE WEATHER AND CIRCULATION OF NOVEMBER 1960[1]

Another November with a Mid-Month Reversal

JAMES F. O'CONNOR

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1. HIGHLIGHTS

Temperatures averaged unseasonably mild throughout most of the United States during November 1960, continuing the warm regime which dominated the country during most of the fall season. This was in sharp contrast to the cold November and fall season of 1959 [1]. In the latter part of the month temperatures in many sections east of the Rockies rose to record high levels for so late in the year. At Rapid City, S. Dak., the average temperature on the 25th was 32° F. above normal, and the maximum was 75° F.

Precipitation totals were in excess of normal in the western States, where many places experienced one of the wettest Novembers on record. In Nevada reservoirs were beginning to refill after two years of drought. In contrast to the West, some large areas east of the Rockies had one of their driest Novembers, particularly the Central Plains and extreme southern Rockies, as well as much of the eastern and southeastern parts of the country.

A marked change in circulation near mid-month was reflected in intensification of storminess over the country in the second half of the month, particularly from the Great Lakes westward. A rapidly deepening storm swept across the Great Lakes on the 15th and 16th, accompanied by high winds, thunder, hail, and tornadoes. In the Far West the weather was quite stormy in the last part of the month with almost daily precipitation in the Pacific Northwest. Heaviest amounts were reported from western Oregon, where flooding caused considerable damage and required evacuation along tributaries of the Willamette river.

Near the month's end, a storm moved out of Nevada on the 27th and swept across the northern Plains, intensifying to blizzard proportions on the 27th and 28th in juxtaposition with a strong crescent-shaped continental-polar High centered over western Canada. High winds (e.g., a record for November of 68 m.p.h. at Duluth, Minn.) and heavy snows in north central areas brought the coldest weather of the season to many places east of the Rockies. For example, Havre, Mont., reported a daily temperature departure from normal of −34° F. on the 28th and Huron, S. Dak., −31° on the 30th.

2. AVERAGE MONTHLY CIRCULATION

The average circulation at 700 mb. for November 1960 (fig. 1) was of the high-index type; i.e., negative height departures from normal dominated the higher latitudes, while positive departures were general at lower latitudes. The only significant exception was the area of blocking and positive height departures over Greenland and the Norwegian Sea.

The most anomalous feature of this average circulation was the strong negative height anomaly near Ireland. This center, together with the blocking to its north, had also been a feature of the previous month's pattern [2] when it was displaced slightly southeastward.

At sea level, the monthly average pattern (not shown) contained a deep cyclonic center as much as 14 mb. below normal west of Ireland, close to the −450-ft. center of height departure at 700 mb. shown in figure 1. This center of action was a manifestation of persistent daily storminess during the month. For example, systems as deep as 960 mb. were observed on 10 days, while storms as deep as 975 mb. were observed on 25 days during the month somewhere in the North Atlantic.

In November there was considerable shearing of the troughs which had been generally of the full-latitude type in October. This was reflected (fig. 1) in troughs at high latitudes superimposed over low-latitude ridges, especially in the Atlantic and Pacific. As a result the zonal index, a measure of the strength of the mid-latitude westerlies averaged over the Western Hemisphere at 700 mb., increased from 9.7 m.p.s. (0.2 m.p.s. above normal) in October to 12.4 m.p.s. (1.9 m.p.s. above normal) in November. The greatest strengthening of the westerlies occurred in the eastern Atlantic, but increases occurred elsewhere in the Western Hemisphere as height falls (relative to normal) at high latitudes were superimposed on rises at lower latitudes, as shown in figure 2.

The height anomaly difference pattern between October and November over North America (fig. 2) is also of

[1] Articles describing the weather of December 1960 and January and February 1961 will appear in the March, April, and May, 1961 issues, respectively, of the *Monthly Weather Review*.

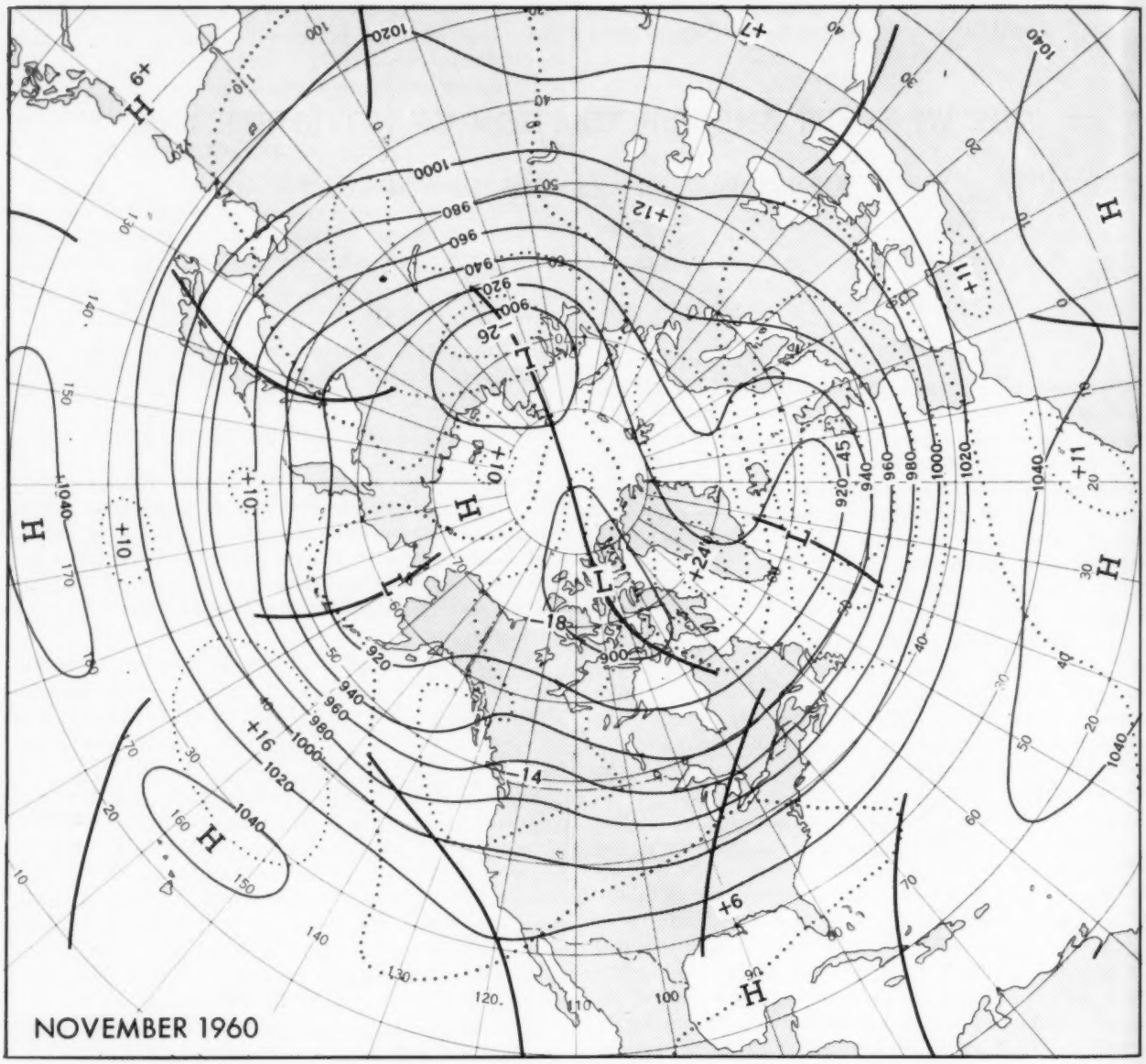


FIGURE 1.—Mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for November 1960. High index was the outstanding feature of the circulation with negative departures at high latitudes and positive departures at lower latitudes.

interest in connection with the changes of weather from October to November. The general trend over the United States shown in this pattern, i.e., falls in the West and rises in the East, was toward more southerly (or less northerly) components of the average flow. This favored warmer temperatures, relative to normal, than the previous month, and increased precipitation. A computation of the temperature anomaly class changes for 100 stations distributed throughout the contiguous United States showed that 41 percent warmed from 1 to 2 classes, while 44 percent remained in the same class (out of five). This represents unusually high persistence from October to November. A similar abnormality occurred last November [1], when 85 percent of the country did not change by more than one class. For precipitation, the northern and western sections reported heavier precipitation than in the previous month, while most of the remainder of the country became drier, except in the Kentucky-Tennessee area.

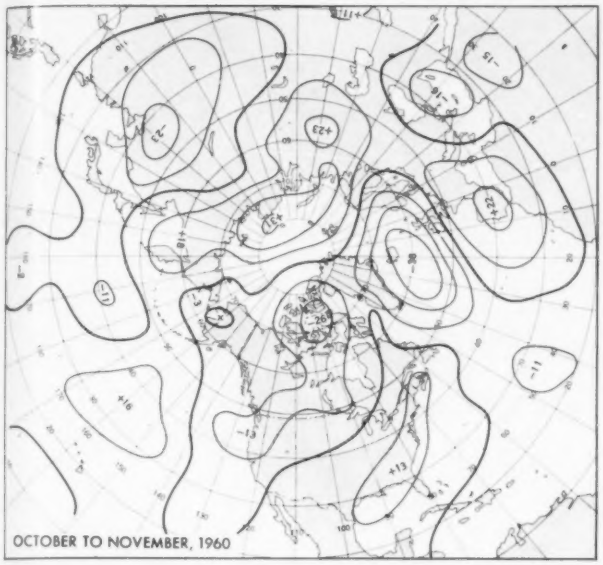
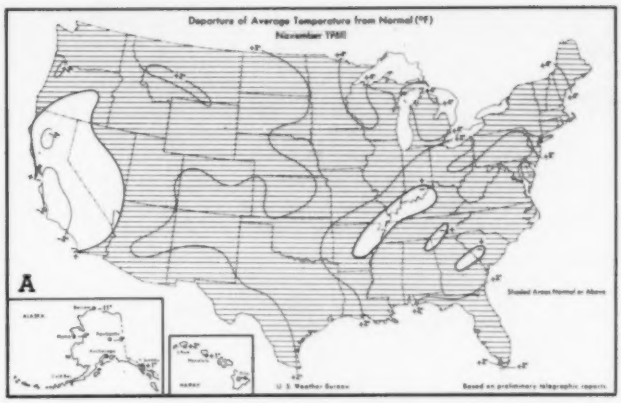


FIGURE 2.—Difference (in tens of feet) between the mean monthly 700-mb. height departures from normal of October and November 1960. Falls in the Pacific Northwest and rises in the southeastern United States produced anomalous southerly or southwesterly components of the average flow over most of the country and general warming, relative to normal, from October.


Departure of Average Temperature from Normal (°F)
November 1960
A
Shaded Areas Normal or Above
U. S. Weather Bureau
Based on preliminary telegraphic reports

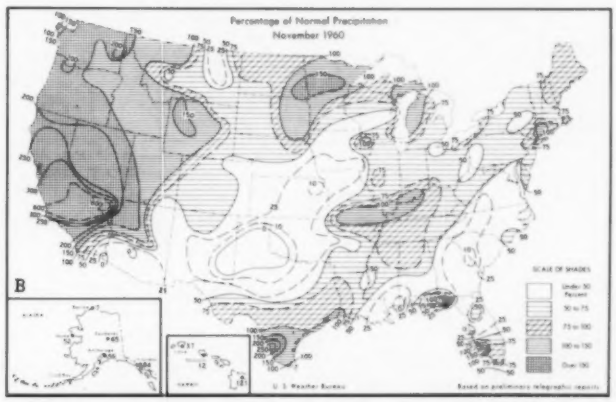


FIGURE 3.—(A) Temperature departure from normal (° F.) for November 1960. (B) Percentage of normal precipitation for November 1960. (From [4].)

3. AVERAGE NOVEMBER WEATHER

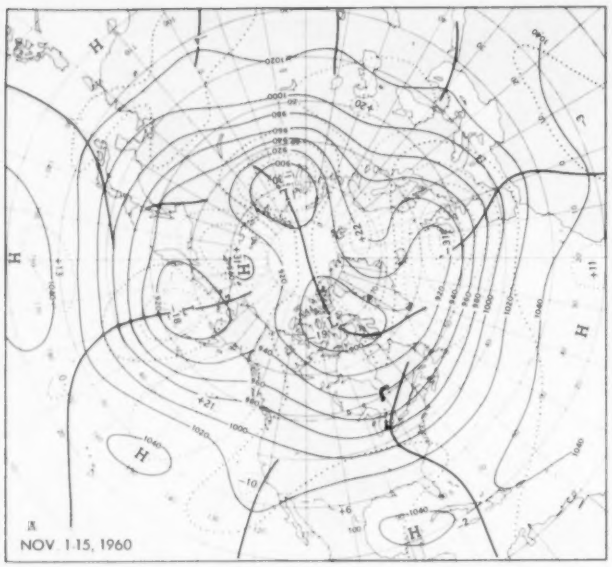
Surface temperatures during November averaged up to 4° F. above normal over most of the contiguous United States and Hawaii, but below normal over most of California and Alaska (fig. 3). The generally mild weather can be explained by the prevalence of anomalous southwesterly components of average flow, as shown by the height departure pattern in figure 1.

Precipitation (fig. 3) averaged heavier than normal in the western United States where many stations reported one of the snowiest Novembers on record. The wetness in the West was related to the deeper than normal trough off the Pacific Coast of North America and to frequent, and at times intense, daily storminess which propagated inland periodically from this trough. Very heavy precipitation in southern California and Nevada occurred early in the month in association with a strong cutoff Low aloft over this area. Although precipitation in the Mississippi Valley was mostly less than normal, nevertheless it stands out in figure 3 in contrast to the dryness in the Plains and in the East. This precipitation was associated with a mean trough in the area (fig. 1) and was produced by daily troughs of large amplitude crossing this region at about weekly intervals, on about November 1, 9, 15, 23, and 28. The troughs of the 1st, 15th, and 28th were associated with deep surface systems

4. THE MID-MONTH REVERSAL

Although this November exhibited more than normal persistence from the previous month, especially in temperature, the circulation within the month was characterized by considerable variability. The intramonthly variability is best portrayed by the patterns of average circulation and temperature for the two half-months, shown in figures 4 and 5, and by the height differences between the first and last halves of the month at 700 mb., shown in figure 6.

In the first half-month (fig. 4A), a stronger than normal ridge along the west coast of Canada and a deeper than normal trough over the Great Lakes facilitated the deployment of colder than normal polar air from Canada southward over the United States. As a result temperatures averaged below normal (fig. 4B) over most of the country, except for parts of the Southwest. The coldest region in this period, relative to normal, was the Kentucky-Tennessee area, where temperatures are known to be inversely correlated with height departures in western Canada.



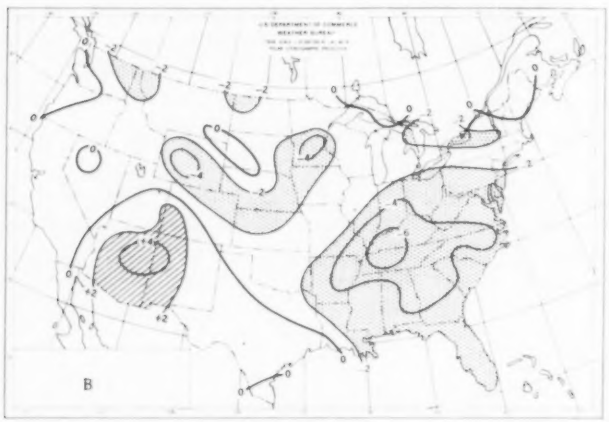
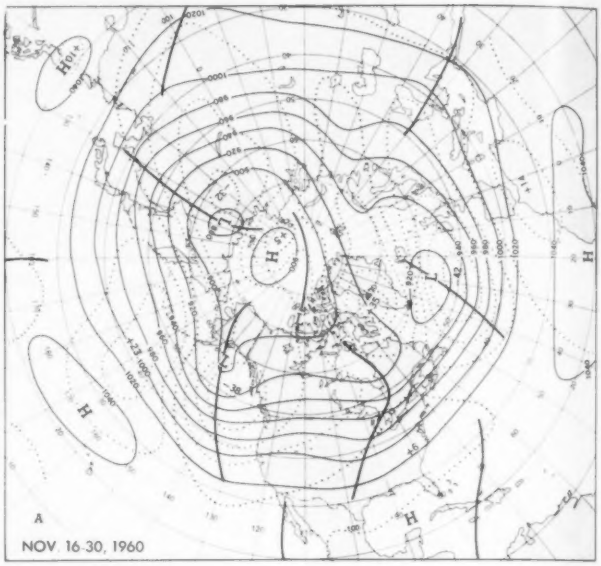


FIGURE 4.—(A) Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for November 1–15, 1960. (B) Surface temperature departure from normal (° F.) for approximately same period as (A). Ridge along west coast and trough in eastern North America produced cooler than normal conditions in most of the United States.



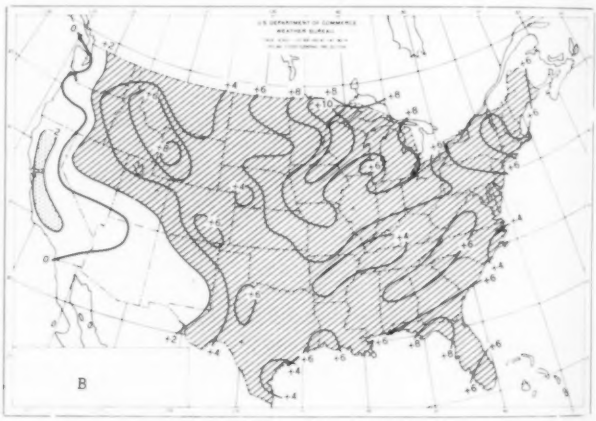


FIGURE 5.—(A) Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for November 16–30, 1960. (B) Temperature departure from normal (° F.) for approximately same period as (A). Deep trough off west coast was associated with increased storminess and warmer than normal conditions in most of the United States.

In the second half-month strong deepening along and off the west coast of North America from the Yukon southward (fig. 6) resulted in a major change in the circulation as a deep full-latitude trough became established off the west coast of North America (fig. 5A) replacing the ridge which had dominated this area earlier in the month. This deepening occurred in consonance with deepening of the Asiatic coastal trough and ridging in the north-central Pacific and was thus primarily a barotropic manifestation of vorticity propagation.

As a result of realignment of the large-scale waves in the Pacific, abnormal southerly components of the average flow developed over much of North America in the last half of the month. In consequence of this change, a marked reversal in weather occurred over the continent, as reflected in warming over most of North America (fig. 5B), in contrast to cool conditions earlier in the month.

5. THE INDEX CYCLE

Figure 7 shows the variation of the 700-mb. westerlies (5-day averages) which occurred this fall in three latitude bands of the Western Hemisphere, together with the normal [2] variation. The subtropical westerlies increased

[2] "Normals" of these indices are averaged from the maps in Weather Bureau *Technical Paper* No. 21 [5]. They are not based on the 30-year period recognized for climatological normals.

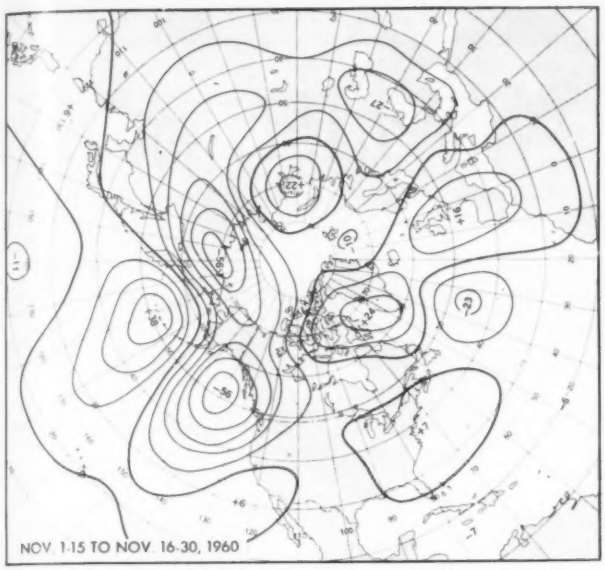


FIGURE 6.—Mean 700-mb. height changes (tens of feet) between first and last halves of November 1960 (figs. 4A and 5A). Height rises in the Central Pacific and falls off the west coast of North America produced a marked change in the mean flow.

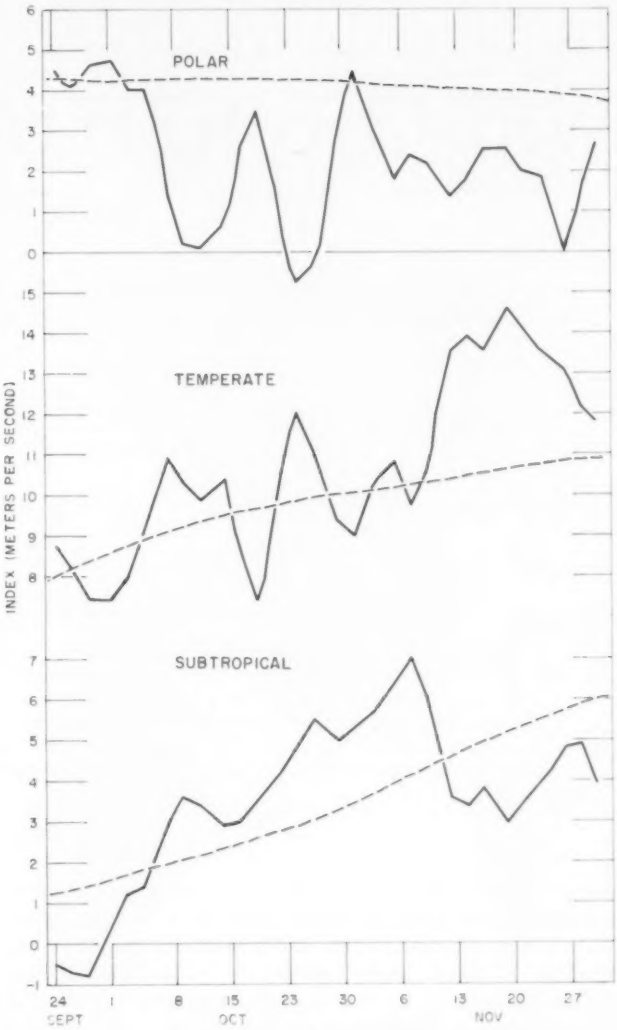


FIGURE 7.—Time variation of 5-day mean 700-mb. indices in meters per second for the western zone of the Northern Hemisphere (0–180° W.). Subtropical index applies between latitudes 20° N. and 35° N., temperate index between 35° N. and 55° N., and polar index between 55° N. and 70° N. Values are for 5-day periods ending on dates indicated. "Normal" indices (dashed lines) averaged from maps of [5].

rapidly after the minimum in late September, reaching their maximum value of 7.0 m.p.s. in early November. The temperate westerlies reached their maximum of 14.6 m.p.s. (4.0 m.p.s. above normal) almost two weeks later. This was the second highest November index since 1945, and was exceeded only by 14.8 m.p.s. in the period November 13–17, 1948. As the normal index curves suggest, the maximum yearly values usually occur later in the year, generally late December or early January. The development of an abnormally strong maximum in the westerlies at mid-latitude frequently signals the beginning of a long decline associated with the winter index cycle. In this case, figure 7 shows a sharp drop in the temperate westerlies subsequent to the November maximum, with the decline still in progress as of mid-December. The abnormally early date of the maximum and subsequent decline this year suggests that the kind of weather normally associated with the winter season commenced early.

As was observed with the maxima in December 1959 and again in April 1960 just prior to major reversals in the trend of the indices [3], the index maximum at mid-latitudes this month lagged the subtropical maximum by about two weeks. In addition it was simultaneously associated with increased positive values in the subtropics of latitudinally averaged height anomalies in the western zone of this hemisphere (not shown). By way of comparison, these positive anomaly averages were as follows: 130 ft. in December 1959 at 35° N., 100 ft. in April 1960 at 30° N., and 90 ft. in November 1960 at 30° N. Maxima of average positive anomalies at these latitudes are, of course, associated with minima of the subtropical westerly index. Thus again we have the suggestion that a minimum in the subtropical index, associated with a positive anomaly maximum in the subtropics, of about 100 ft., may be a signal for a major reversal in the index cycle. Furthermore, as occurred in late December 1959, April 1960, and this month also, the index reversal is likely to be accompanied by a major upheaval in long-wave and weather patterns, manifested initially at the surface by violent storm activity traversing the country from southwest to northeast.

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